Table-top EUV/Soft X-ray Source and Wavefront Measurements at Short Wavelengths

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Dept.
“Optics / Short Wavelengths”

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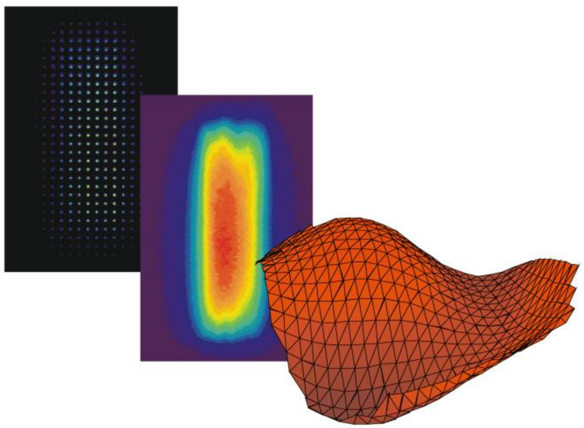
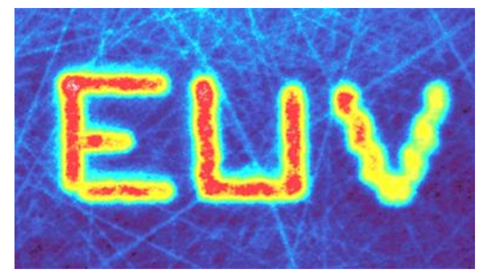
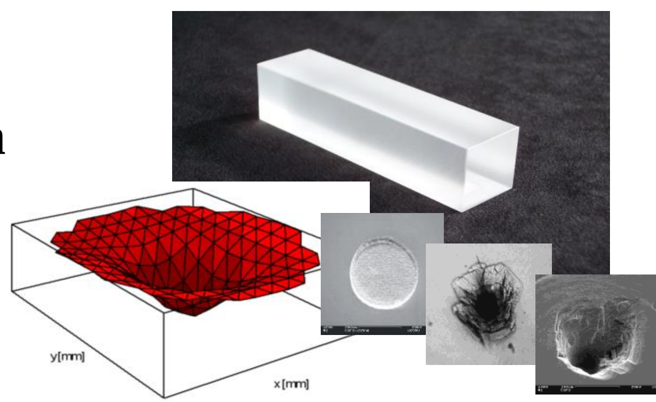


- **Optics test** (351…**193 nm**)
  - *(Long term) degradation (10^9 pulses)*
  - *Non-linear processes*
  - *LIDT*
  - ***Absorption** / Scatter losses*
  - *Wavefront deformation*



- **Beam propagation**
  - *Wavefront*
  - *coherence*
  - *M²*



- **EUV/XUV technology**
  - *Source & Optics*
  - *Metrology*
  - *Material interaction*

Laser plasma source for extreme UV and soft x-ray radiation

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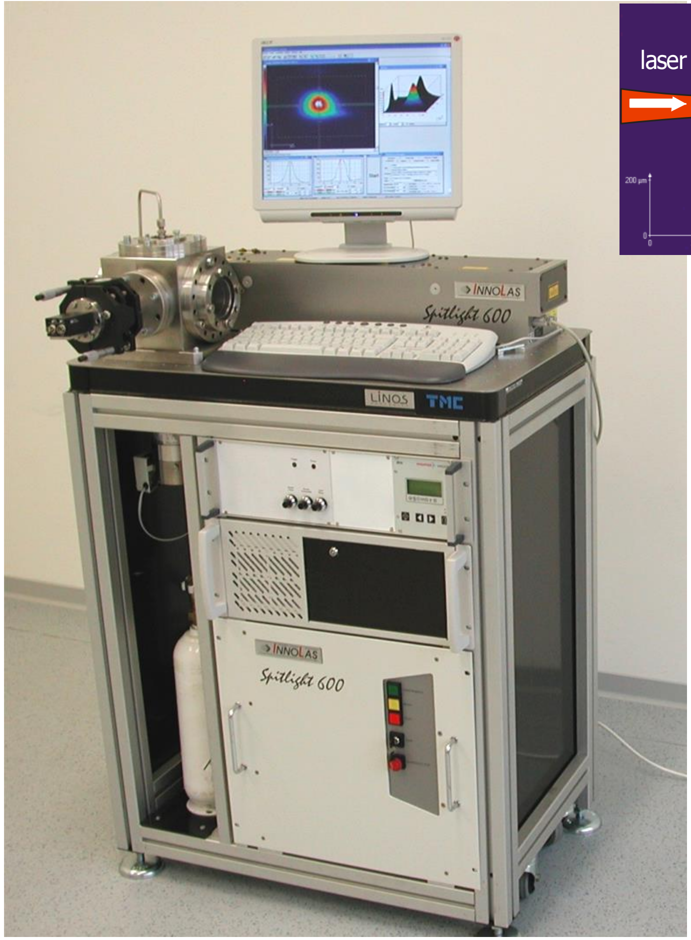
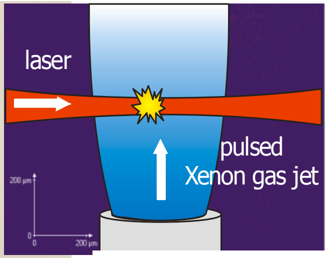
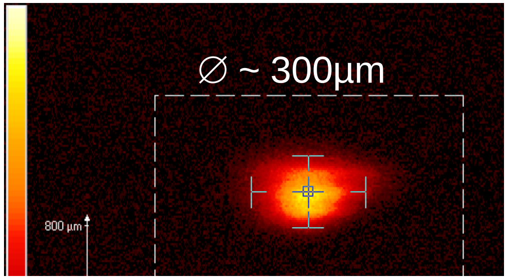
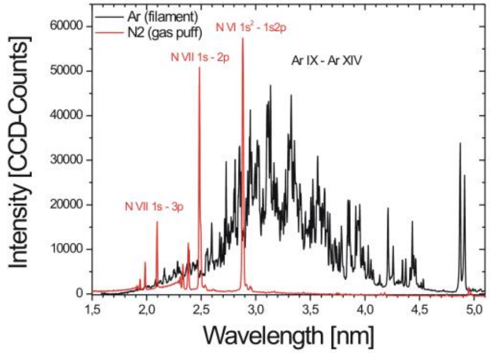


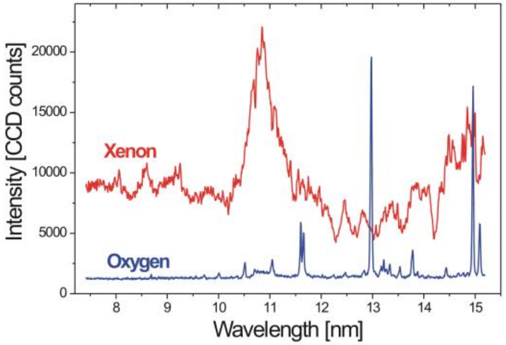


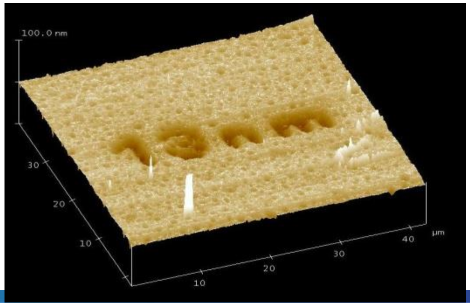


XUV: λ=1…10nm



EUV: λ= 10…20nm





- compact
- low debris
- long-term stable
- versatile

- Univ. Prag
- Univ. Göttingen
- Max-Planck Inst.

LLG-Activities Based on LPP Source

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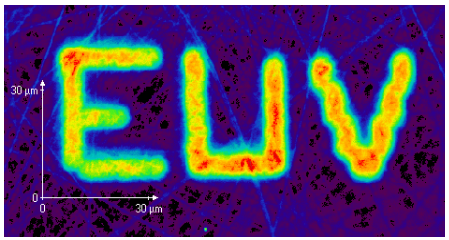
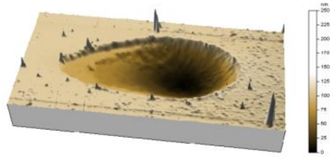
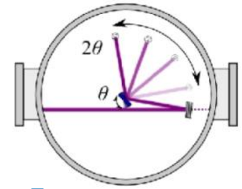
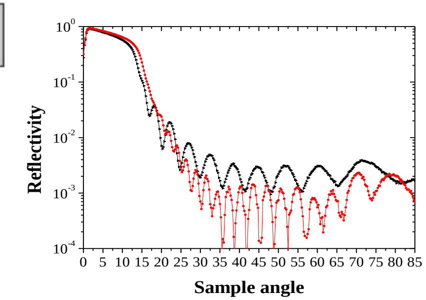
- Direct structuring

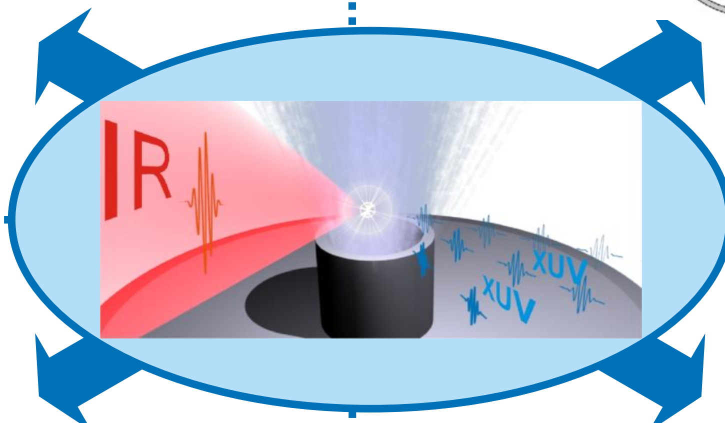


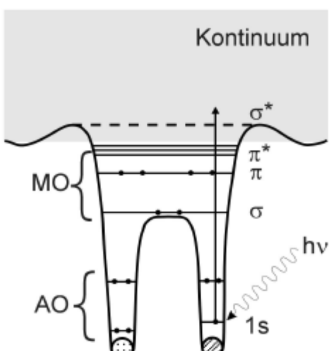


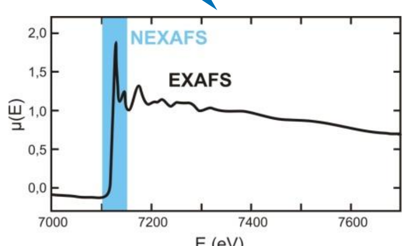
- EUV reflectometry



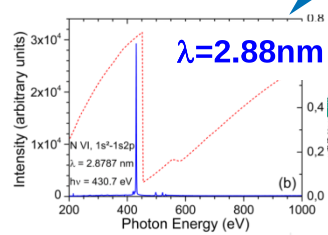


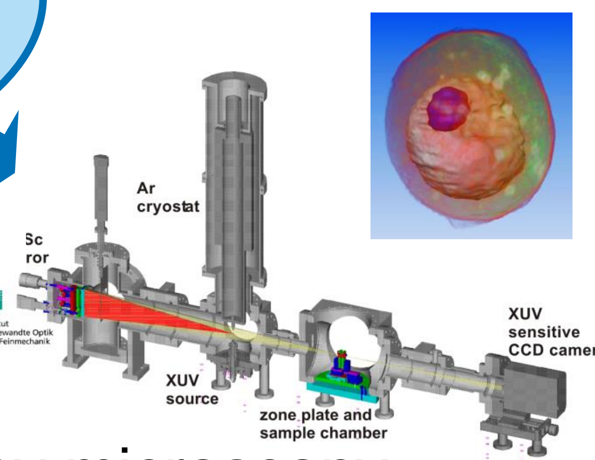






- NEXAFS spectroscopy

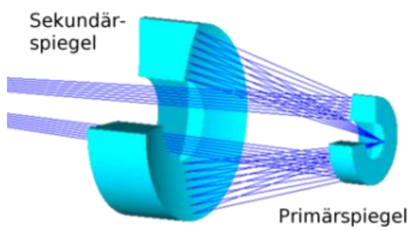


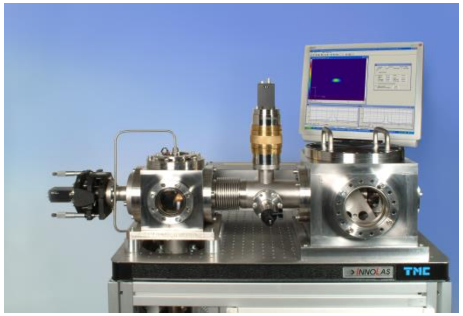


- Soft x-ray microscopy

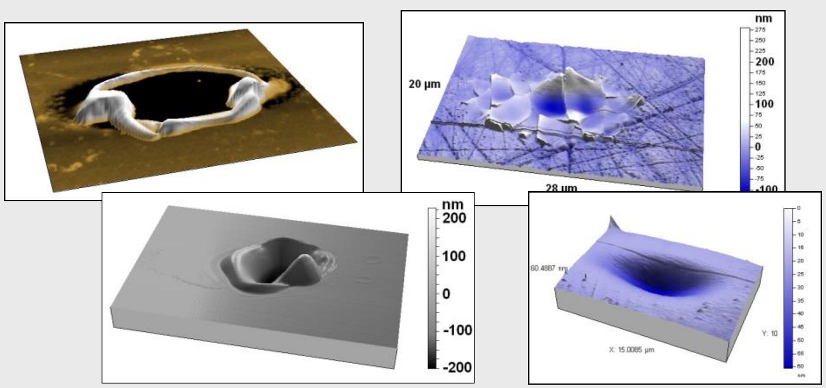
Ablation / damage thresholds @13.5nm

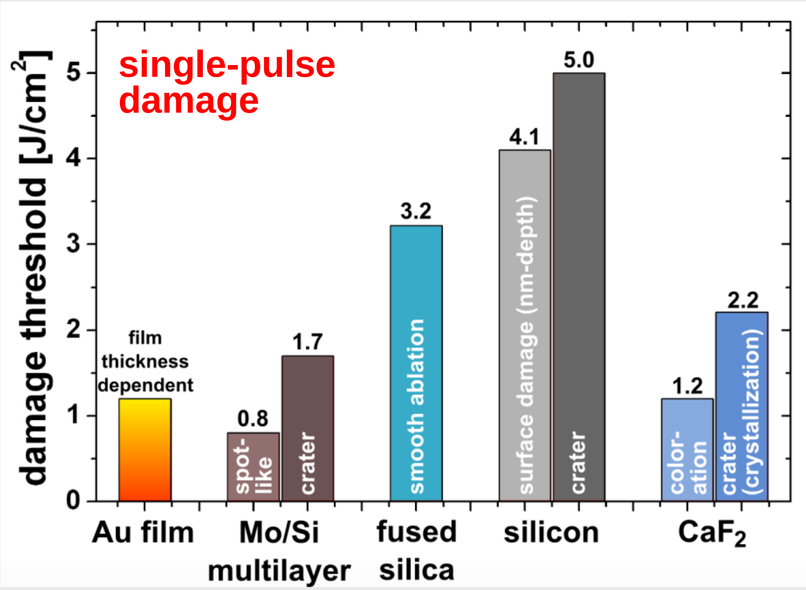
- EUV Schwarzschild objective (Mo/Si):
  - ~ J/cm² @ 13,5 nm





- Damage thresholds of mirrors / substrates





F. Barkusky, K. Mann et al., Optics Express 18, 4347 (2010)

EUV/XUV plasma source

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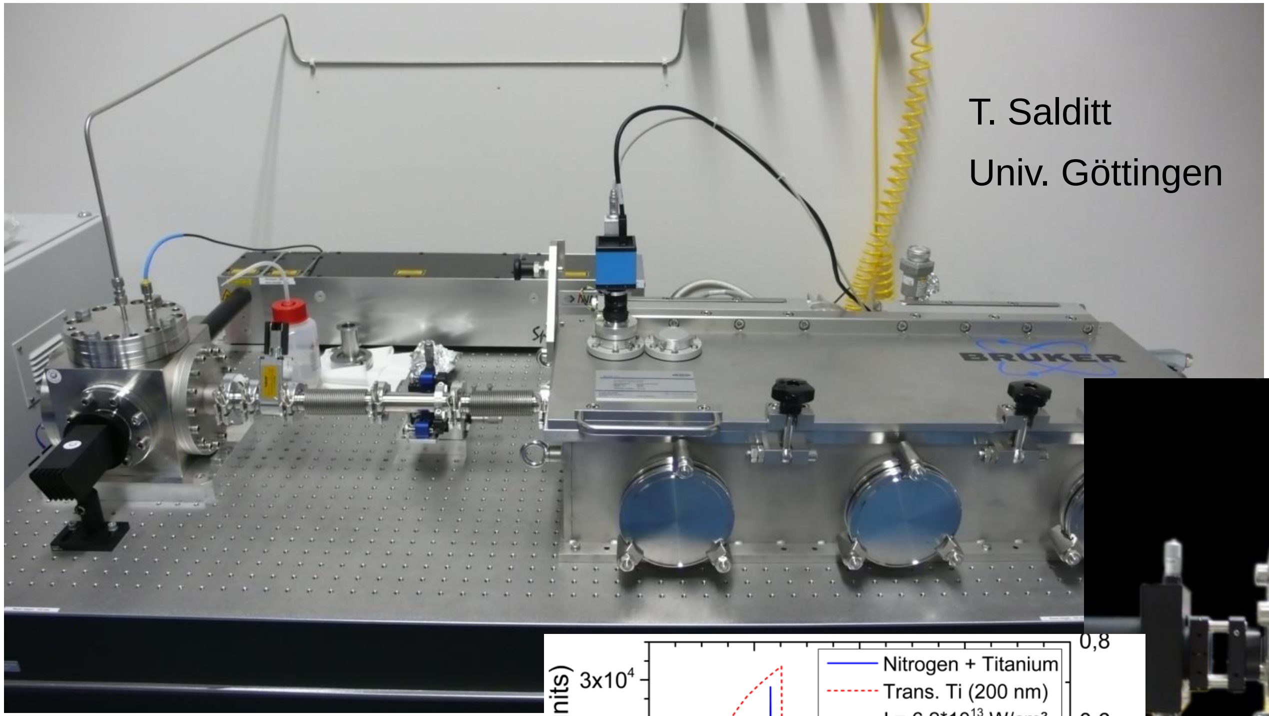
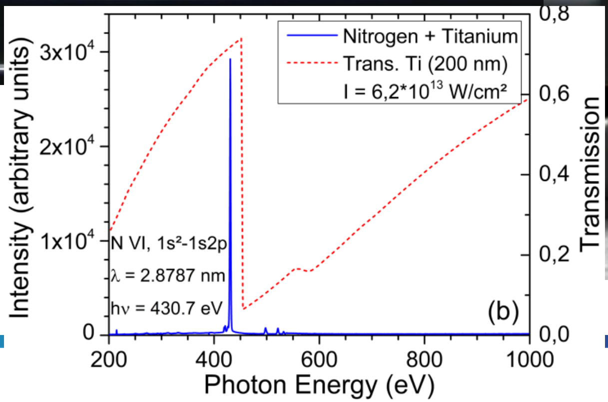


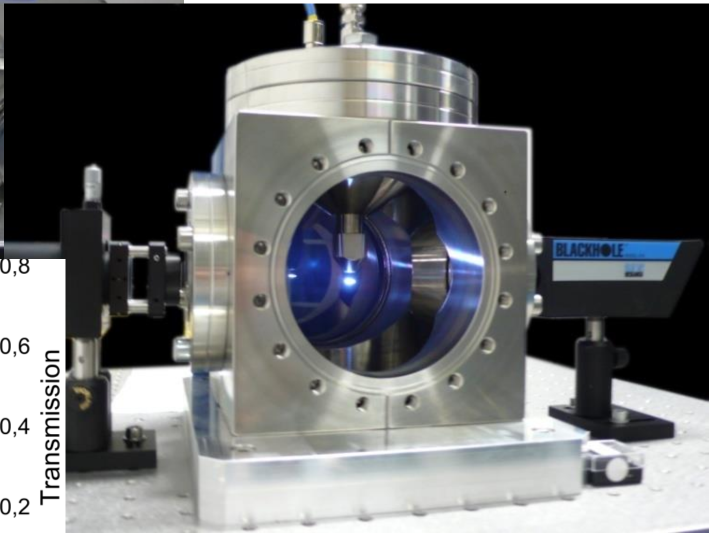
SFB 755
Nanoscale Photonic
Imaging

Isolated Nitrogen line @ λ = 2.88nm

Peak brillance:

$6*10^{17}$ [Ph./(s mrad^2 mm^2 0,1%BW)]





→ Microscopy @ λ = 2.88nm

NEXAFS Spectroscopy in the „water window“:

= Near-edge x-ray absorption fine-structure

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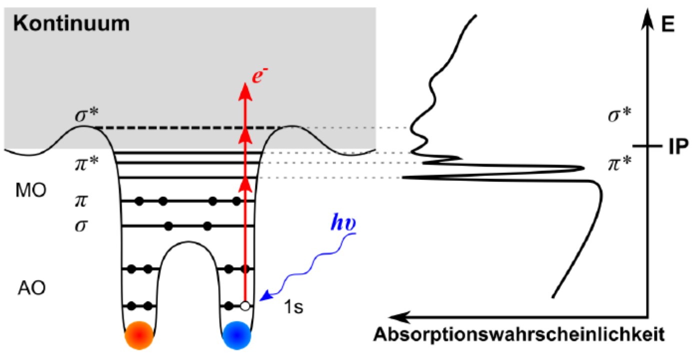
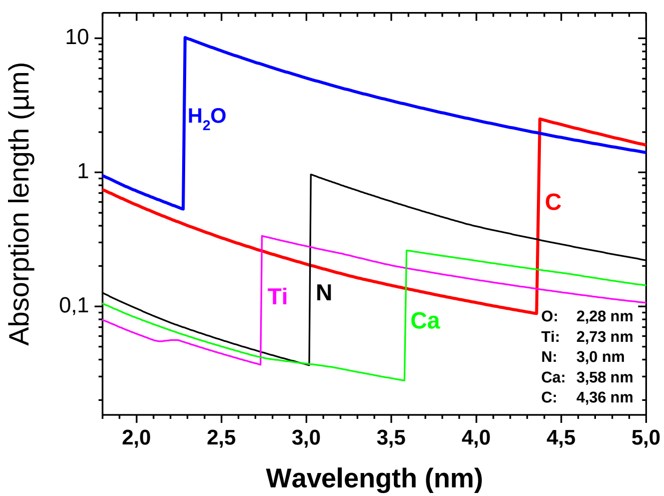


- Excitation of unoccupied molecular orbitals

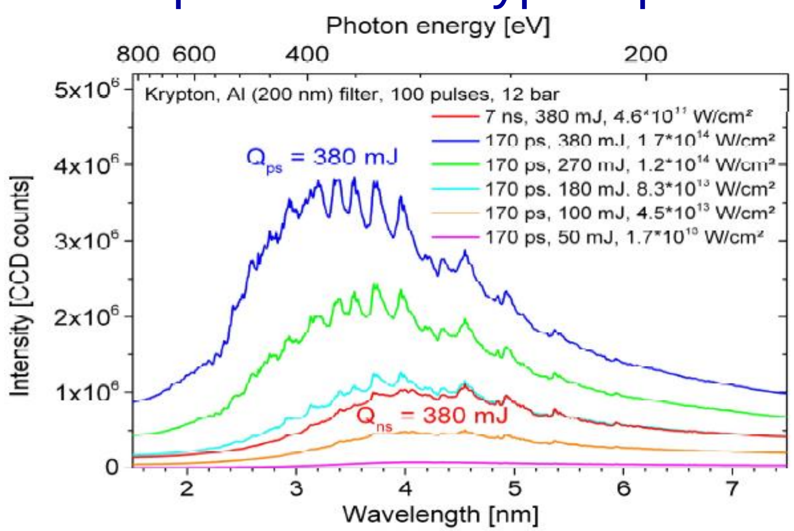
→

- ***„Fingerprint“ of molecules***
- ***surface-sensitive chemical analytics***

- Accessable absorption edges



- Spectrum of Krypton plasma



B, C, N, O, F, S, Ca, Ti, Mn, Fe…

Table-top NEXAFS Spectrometer

λ = 1 …7nm, 10 …20nm

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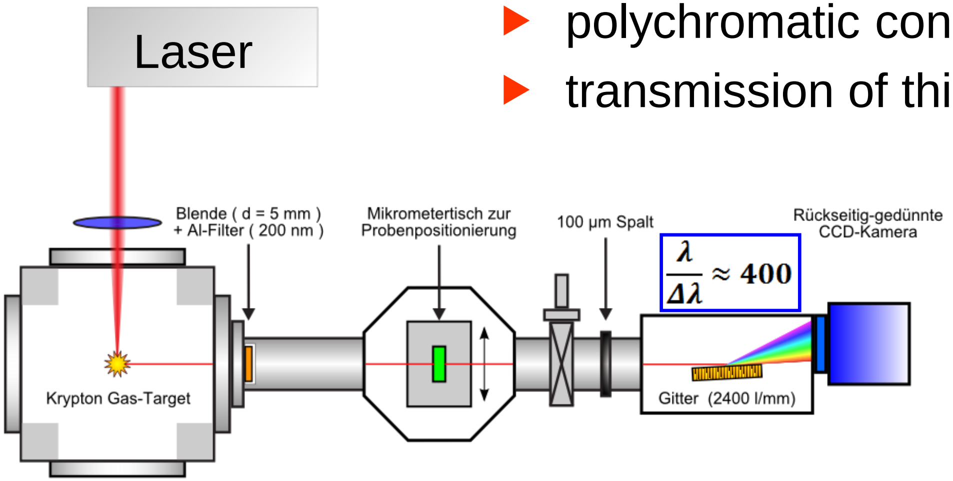
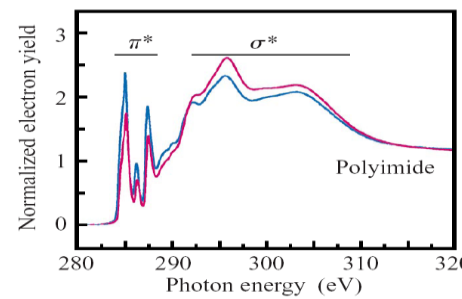
- polychromatic concept („single-shot“)
- transmission of thin samples

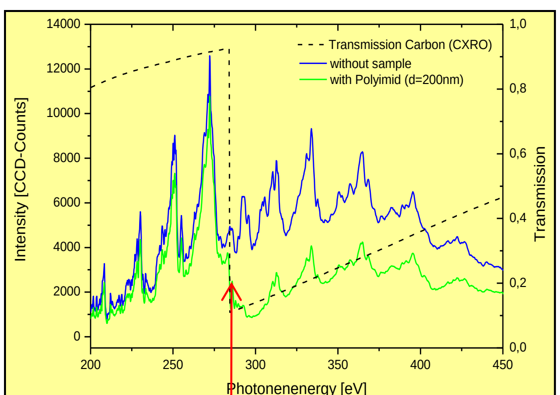


Source sample spectrometer

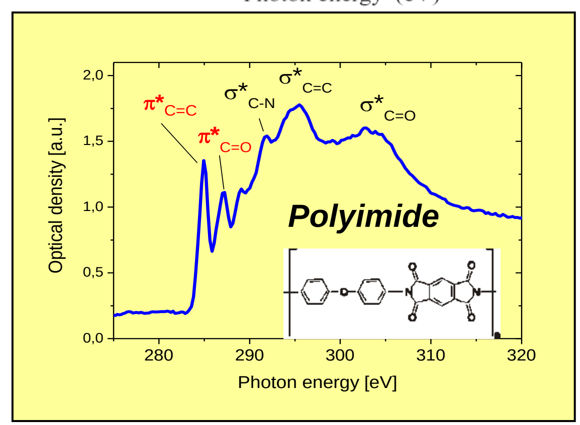


Synchrotron (J. Stöhr)

polyimide sample (d=200nm):



Carbon K-edge



60 laser pulses

C. Peth, K. Mann et al., J. Phys. D **41** (2008) 105202

Compact NEXAFS spectrometer

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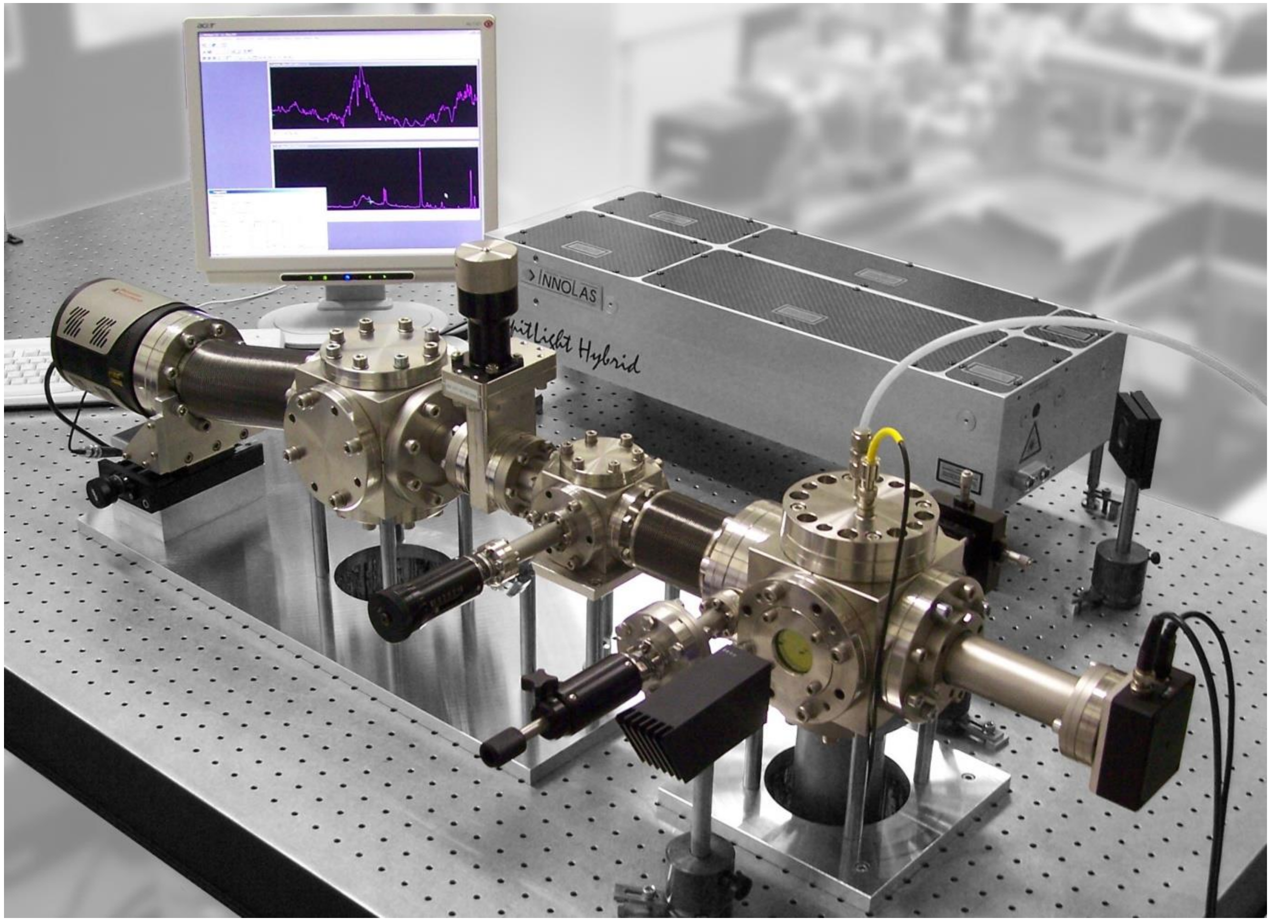
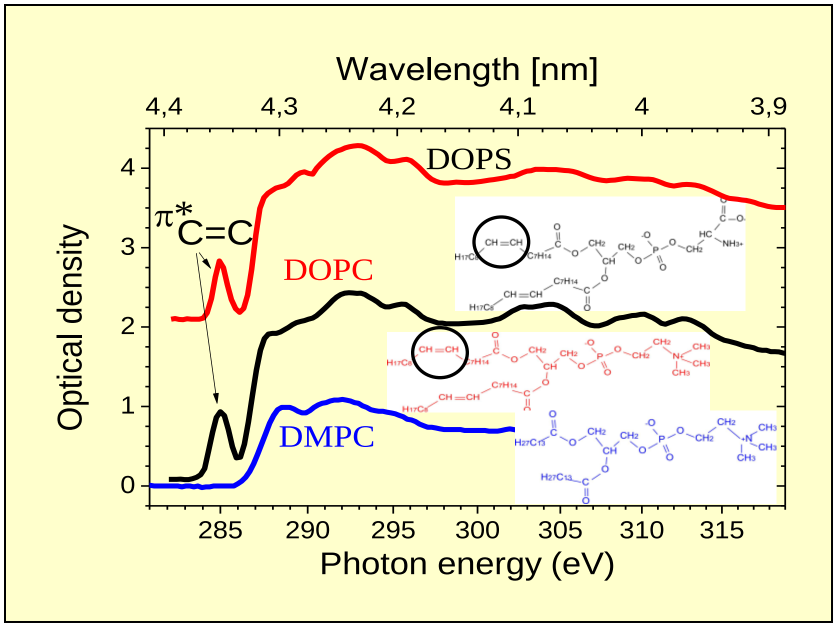
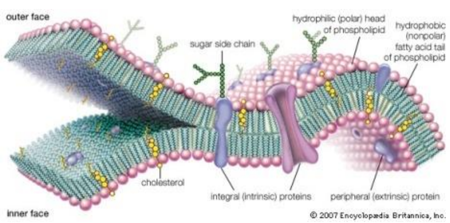


- $\lambda =$ 1 …7nm
  10 …20nm
- pump-probe exp.
- measurement in ambient air

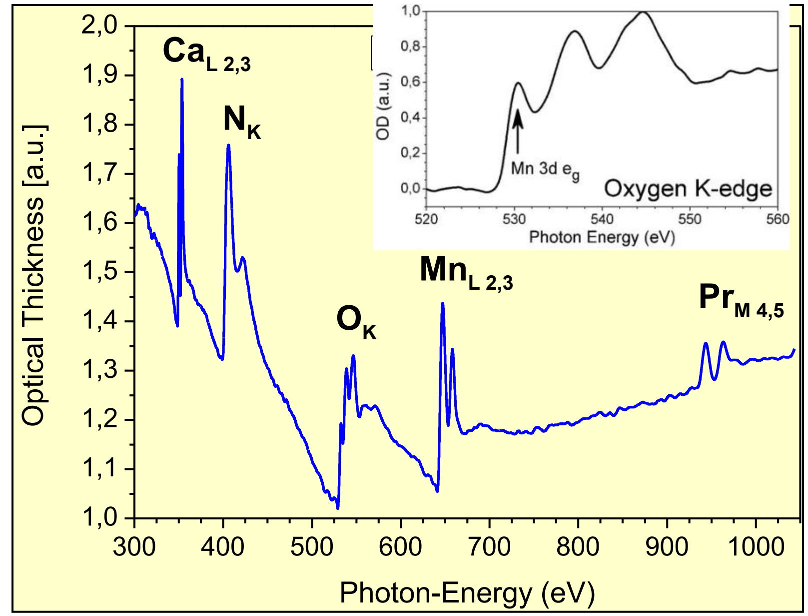
NEXAFS spectroscopy on thin films

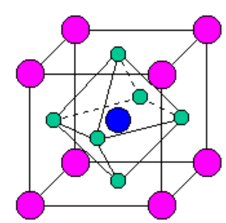
- Lipid membranes (carbon K-edge) (T. Salditt)





- PCMO (Perovskite-type manganate) $Pr_{1-x}Ca_xMnO_3$ (S. Techert)





: Pr, Ca
: O
: Mn

- Every element visible (single shots)
- Pump-probe experiments → phase transitions

E. Novakova, C. Peth, K. Mann, T. Salditt et al.: Biointerphases, **3** (2008) FB44

P. Grossmann, S. Techert, C. Jooss, K. Mann et al.: Rev. Sci. Instr. 2012

NEXAFS at Fe $L_{2,3}$ edge

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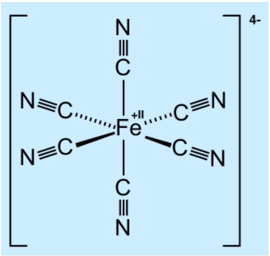
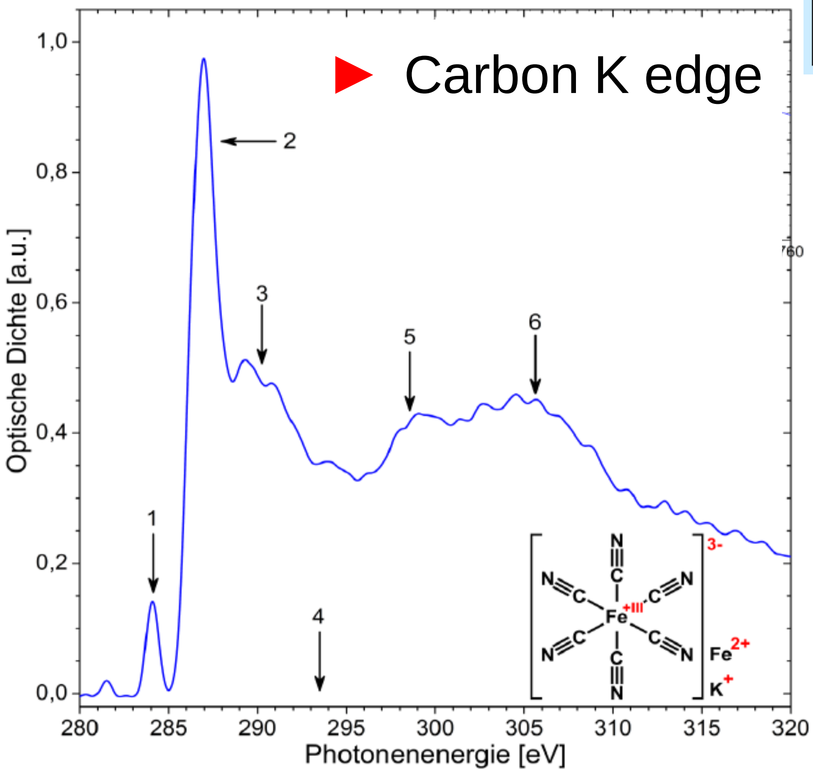
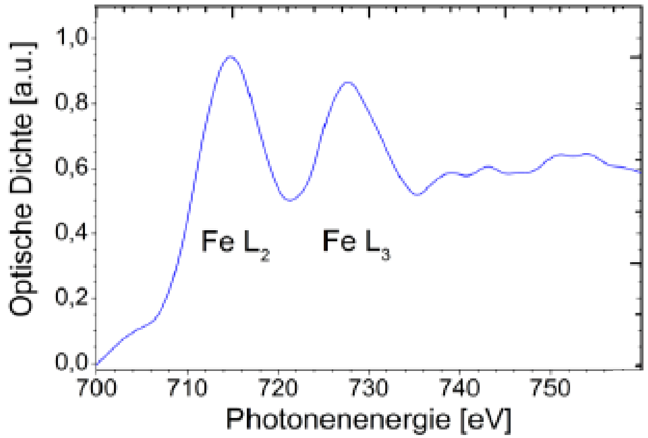
Example:
Prussian Blue



▶ Carbon K edge



▶ Iron $L_{2,3}$ edge



- *Photon energy ~ 720eV*
- *300 laser pulses*

Improvements (1):
Power density: ns → ps laser

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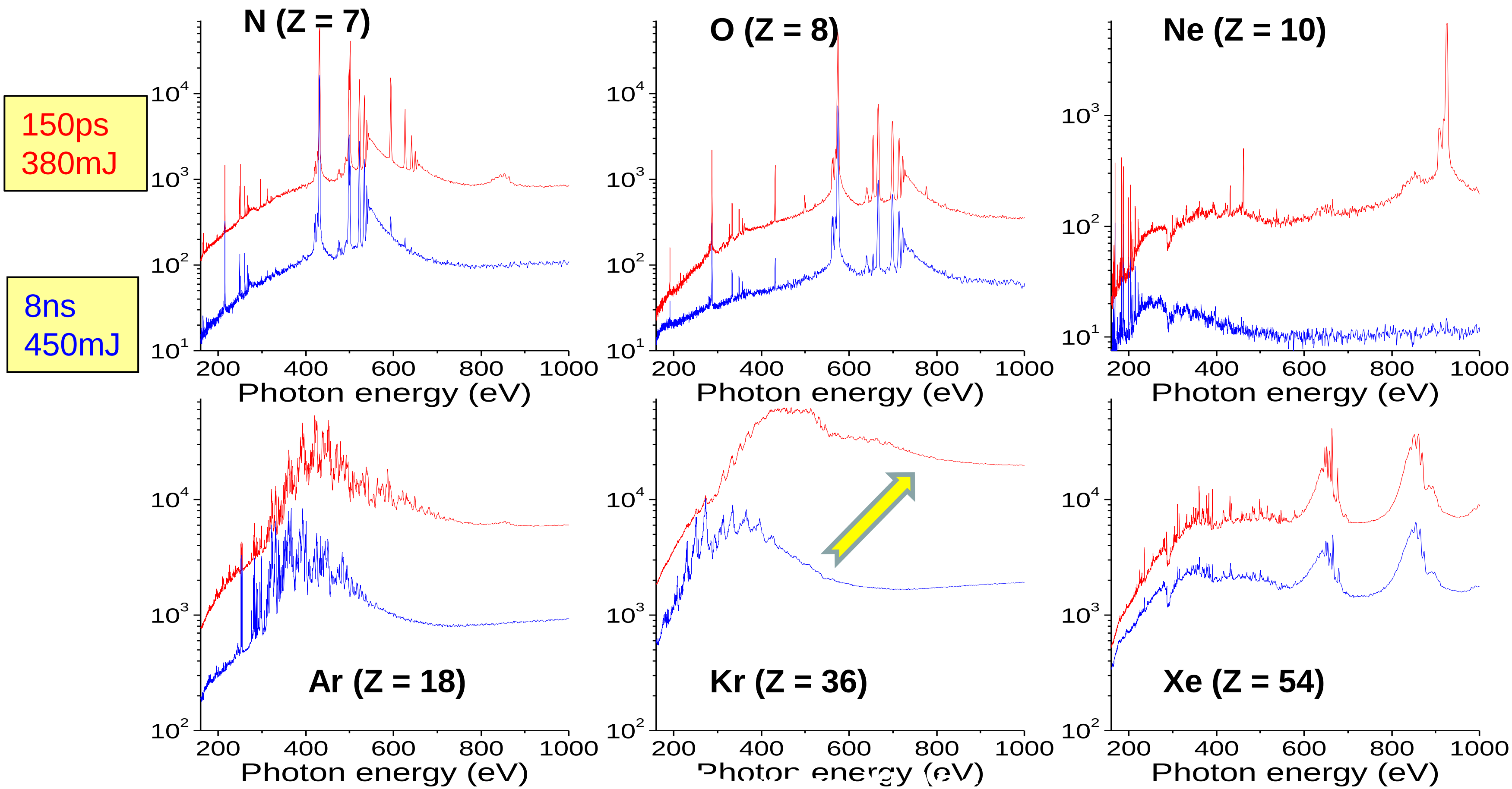
Single pulse spectra:



Peak brillance of isolated N line @ λ = 2.88nm:

6*10^{17} (ns laser) ⇒ 1.2*10^{20} Ph./(s mrad^2 mm^2 0,1%BW)   (ps laser)

Simulation of spectra: Ar

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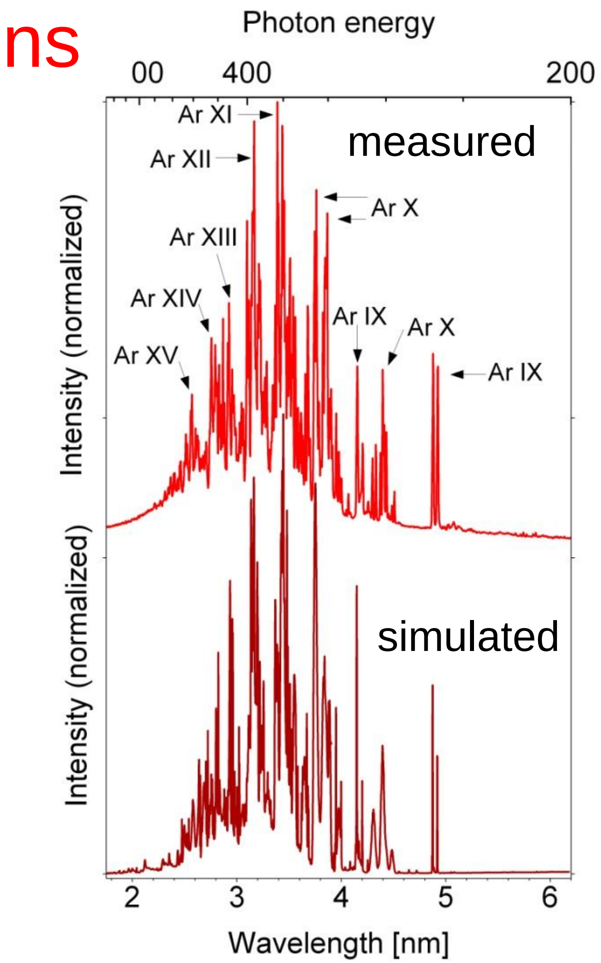

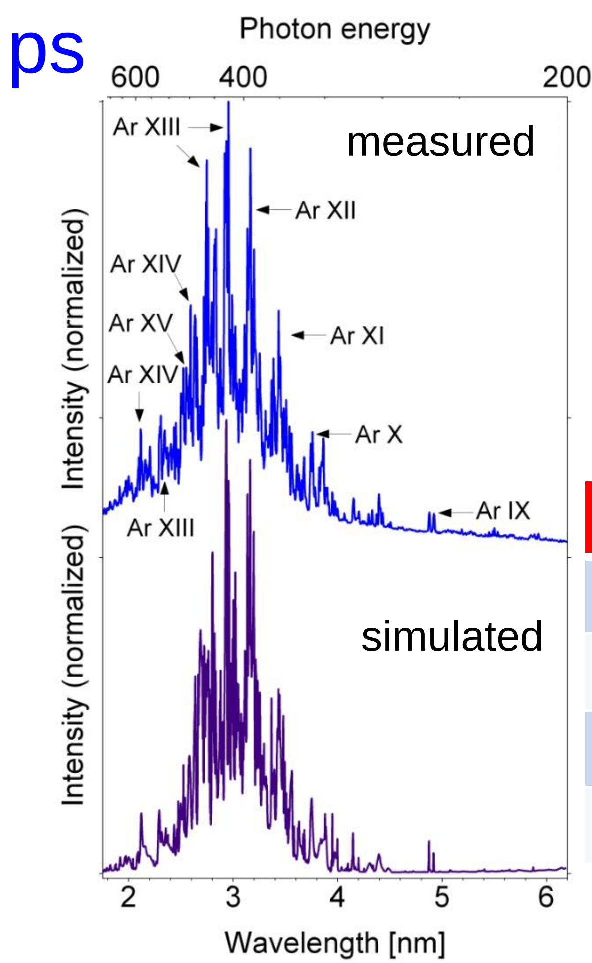

- Calculation with MHD code *PrismSPECT*

ns laser	ps laser
electron temperature [eV]	
50.3	66.3
electron density [10^{19} e/cm³]	
7.0	22.4

M. Müller, K. Mann et al.: Opt. Express ***21*** *(2013)*

Improvements (2):
Plasma generation with barrel shock

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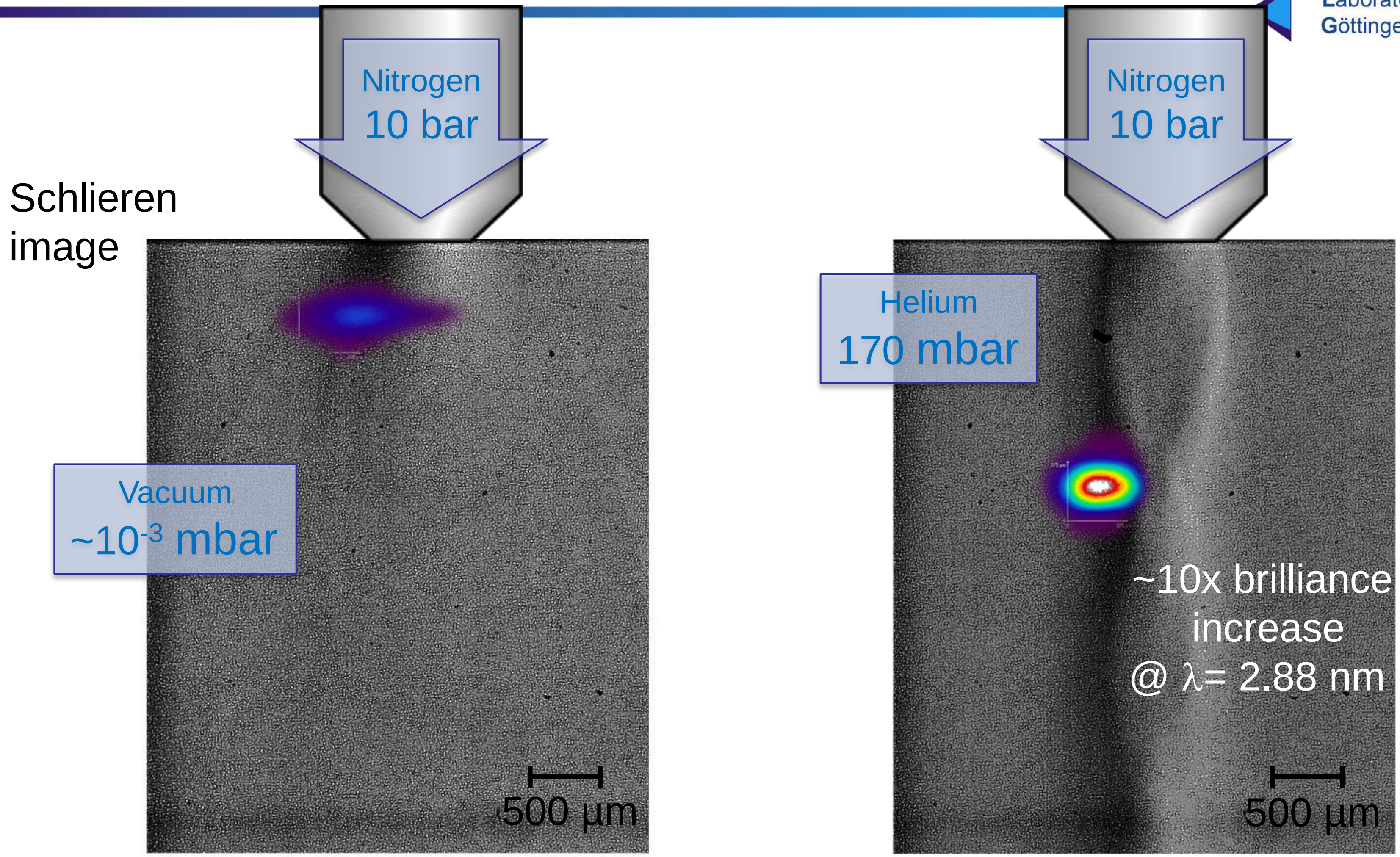

T. Mey, M. Rein, K. Mann, New J. Phys. **14** (2012) 073045

Improvements (3):
Focusing optics for x-ray plasma

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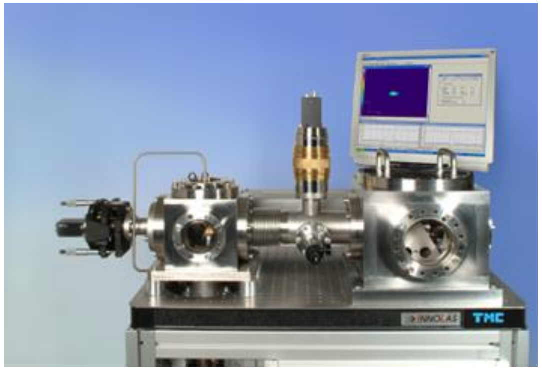
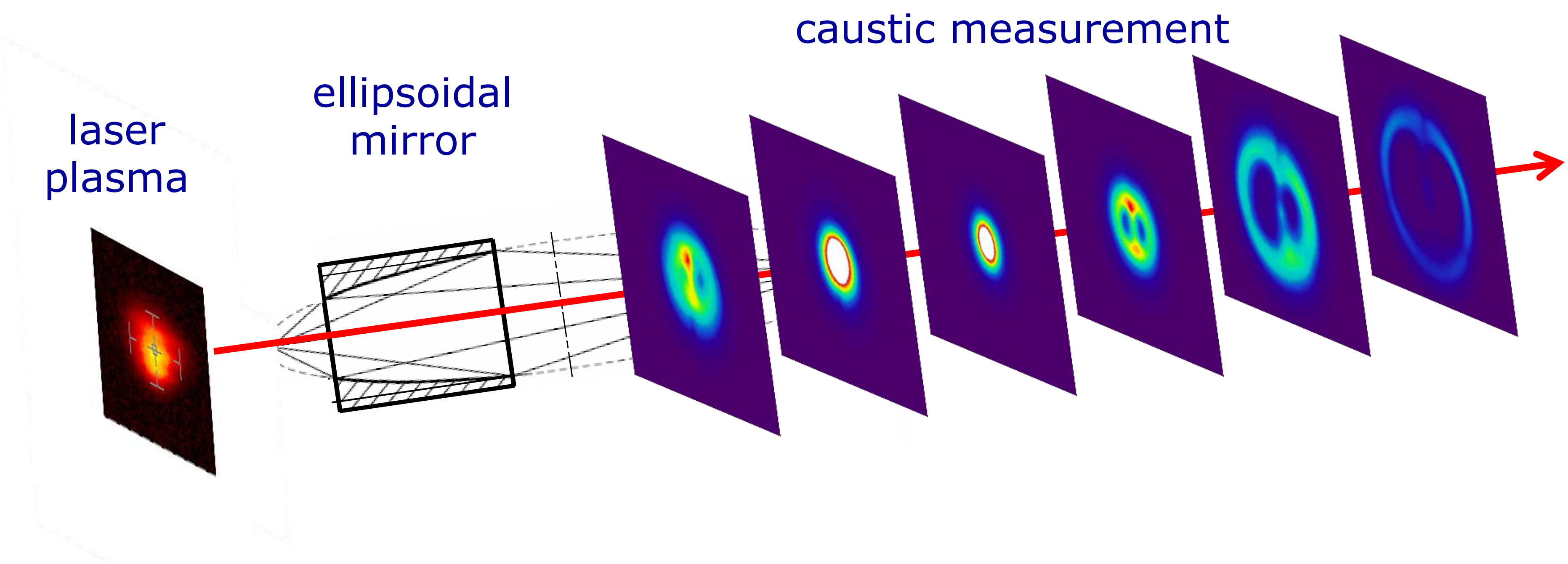


- Nitrogen plasma, λ = 2.88nm (monochromatic)
- grazing incidence ellipsoidal mirror
- $\rightarrow$ focus dia. ~ 500µm



Ablation of PMMA @λ =2.88nm

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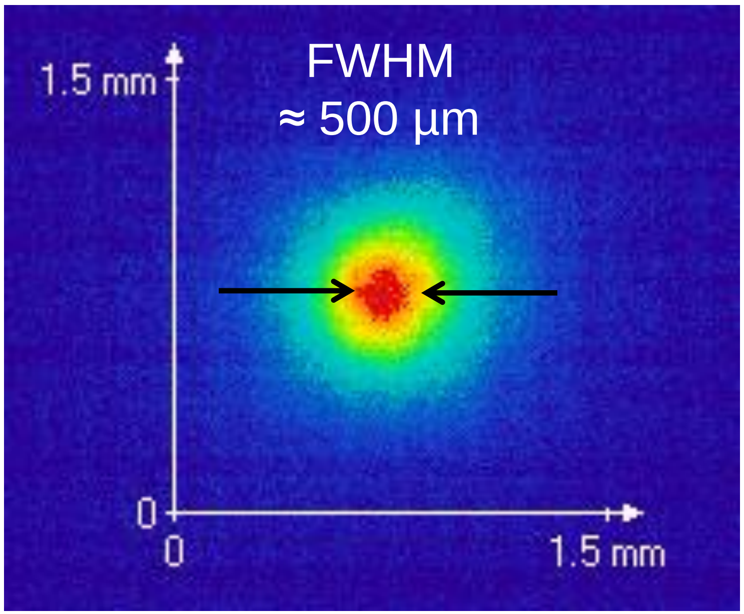
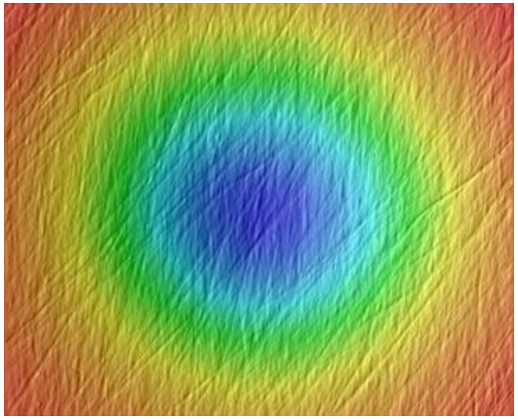
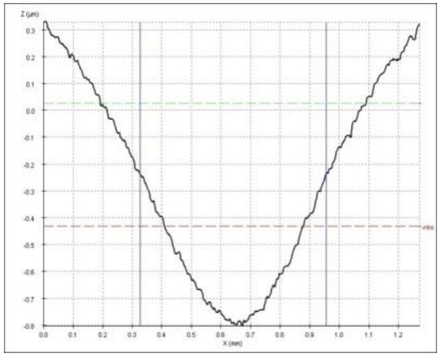


focal spot of elliptical mirror:
~ 1 mJ/cm² @ 2.88 nm
≈ 8.5*10^9 photons/pulse

Kr plasma (3 …6nm): ~ 100mJ/cm²





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Focusing optics for x-ray plasma

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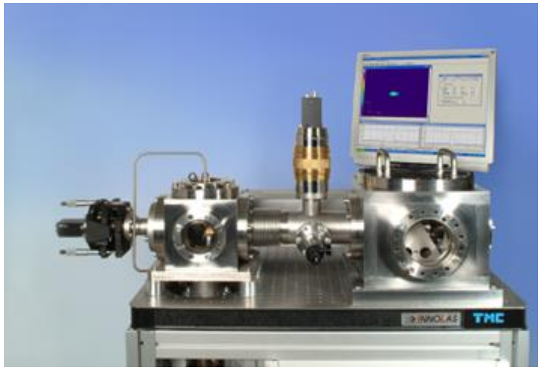

- Nitrogen plasma, λ = 2.88nm (monochromatic)
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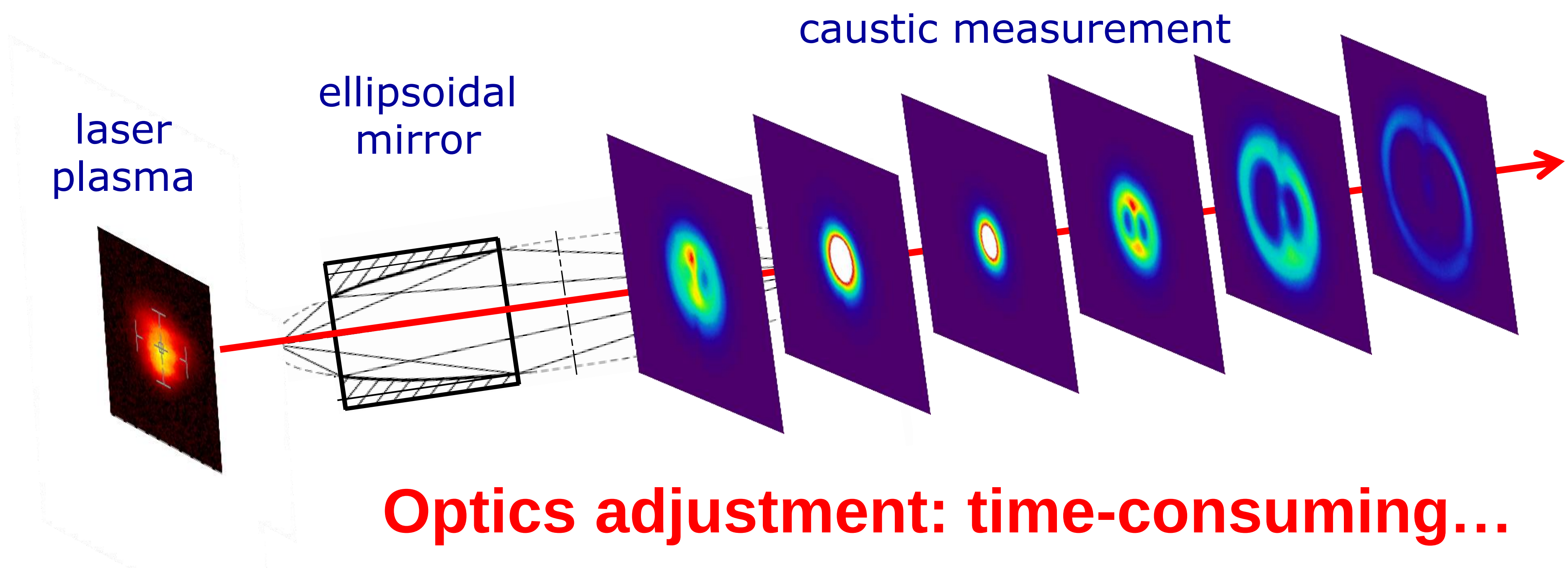
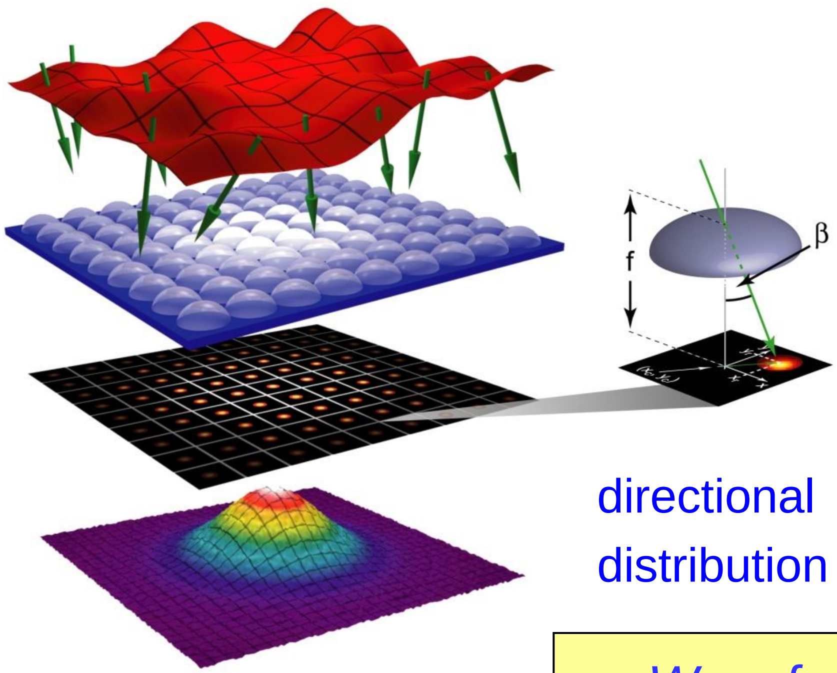


Optics adjustment: time-consuming…

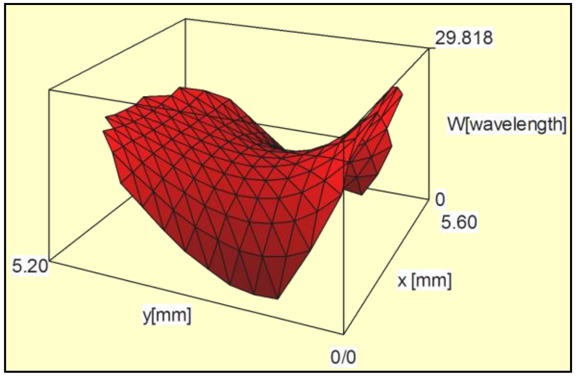
Wavefront measurements
Hartmann-Shack sensor:

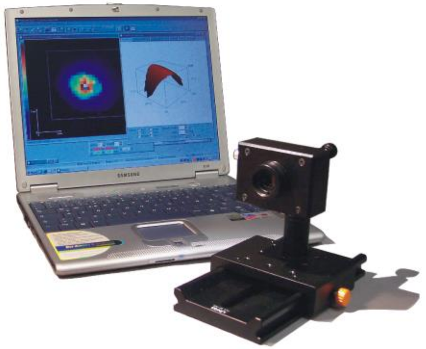


directional
distribution

intensity
distribution

wavefront:





$\Rightarrow$ *Wavefront* w(x,y)

= surface ⊥ Poynting-Vektor S(x,y)

(ISO 15367-2)

Beam characterization of FLASH

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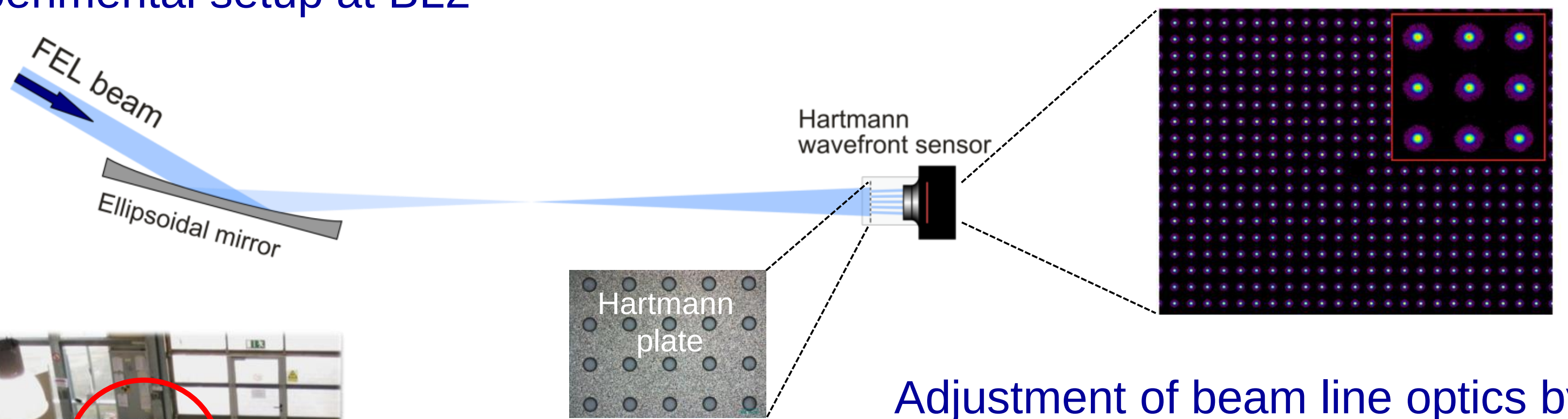
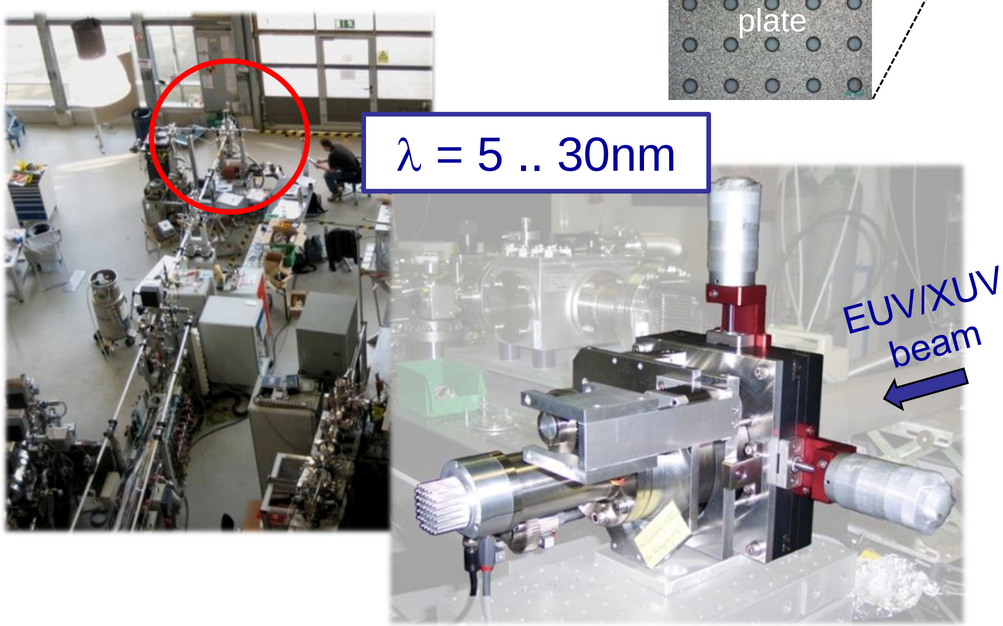
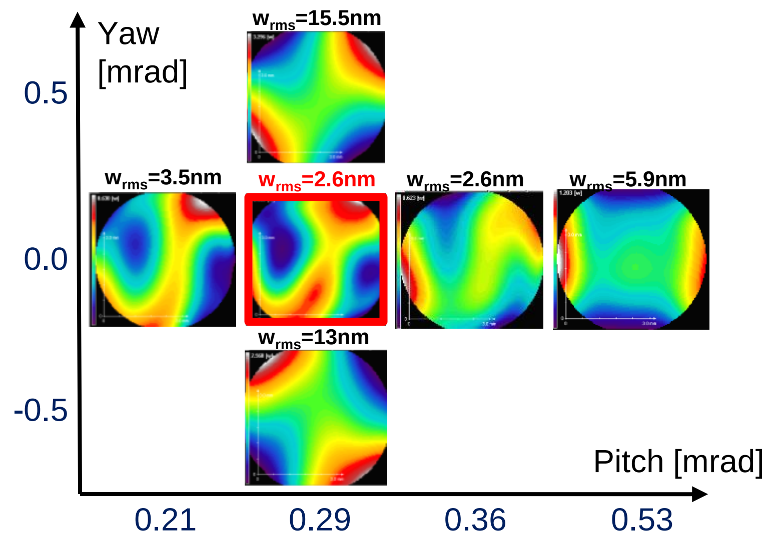
Experimental setup at BL2





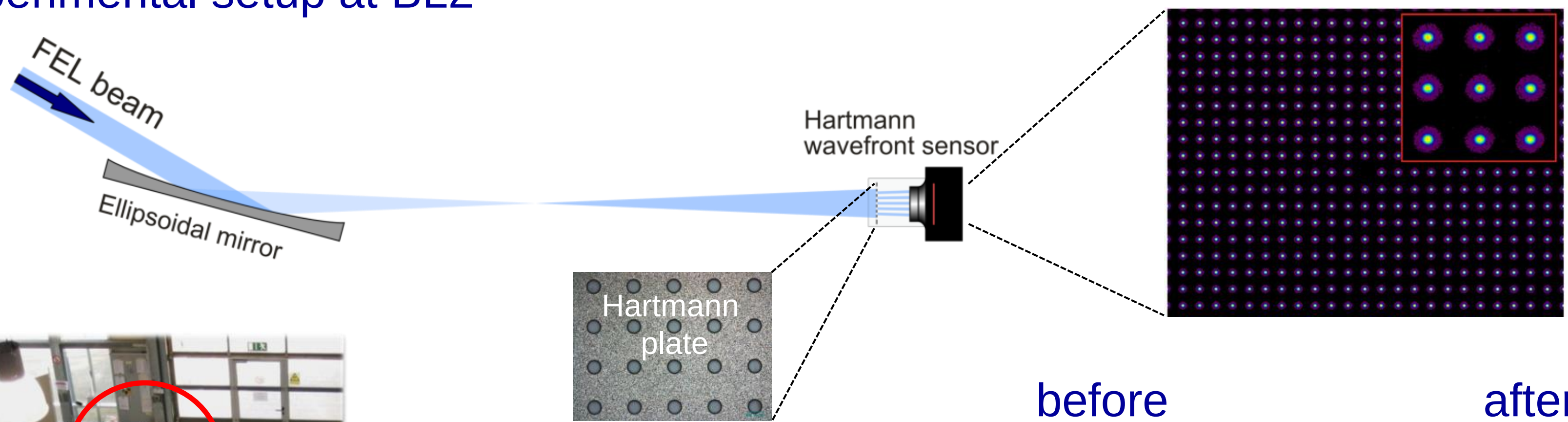
Adjustment of beam line optics by online wavefront monitoring

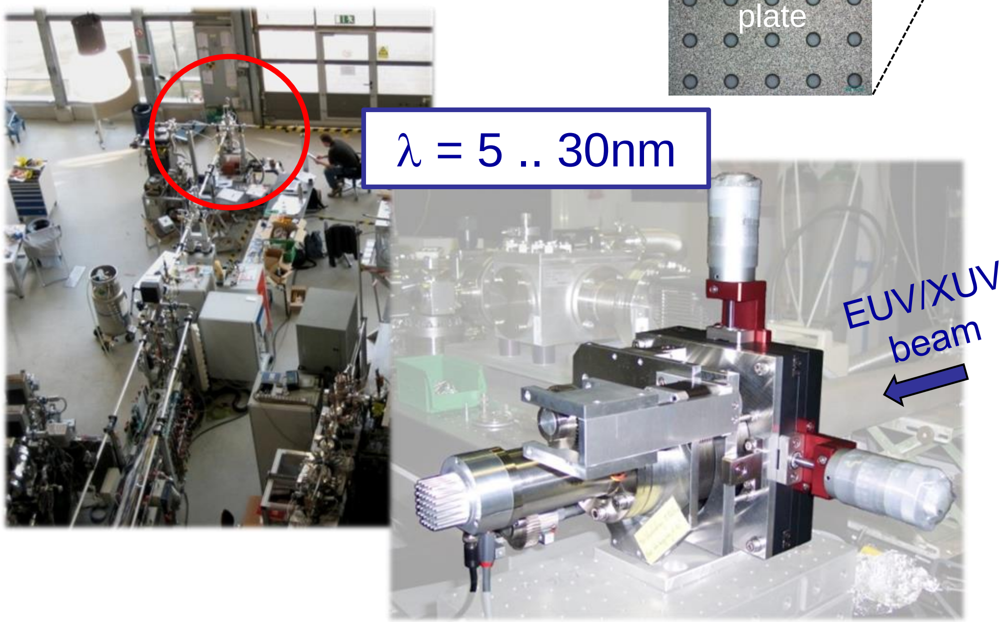


[1] B. Flöter *et al*, *Beam parameters of FLASH beamline BL1 from Hartmann wavefront measurements*, Nucl. Instrum. Meth. A 635 (2011) 5108-5112

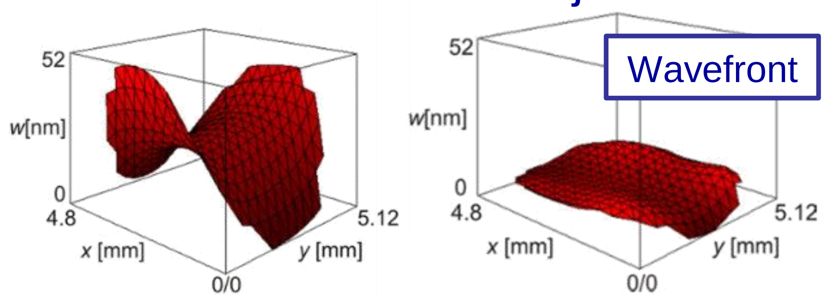
Beam characterization of FLASH

Experimental setup at BL2





before adjustment | after adjustment



w_{rms}~ 10nm | w_{rms}~ 2.5nm ~ λ/10

[2] B. Flöter *et al*, *EUV Hartmann sensor for wavefront measurements at the Free-electron LASer in Hamburg*, New J. Phys. 12 (2010) 083015

Beam parameters from Hartmann data FLASH BL2 @λ=7nm

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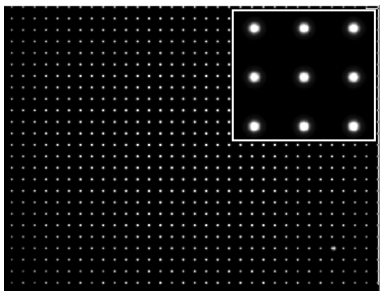
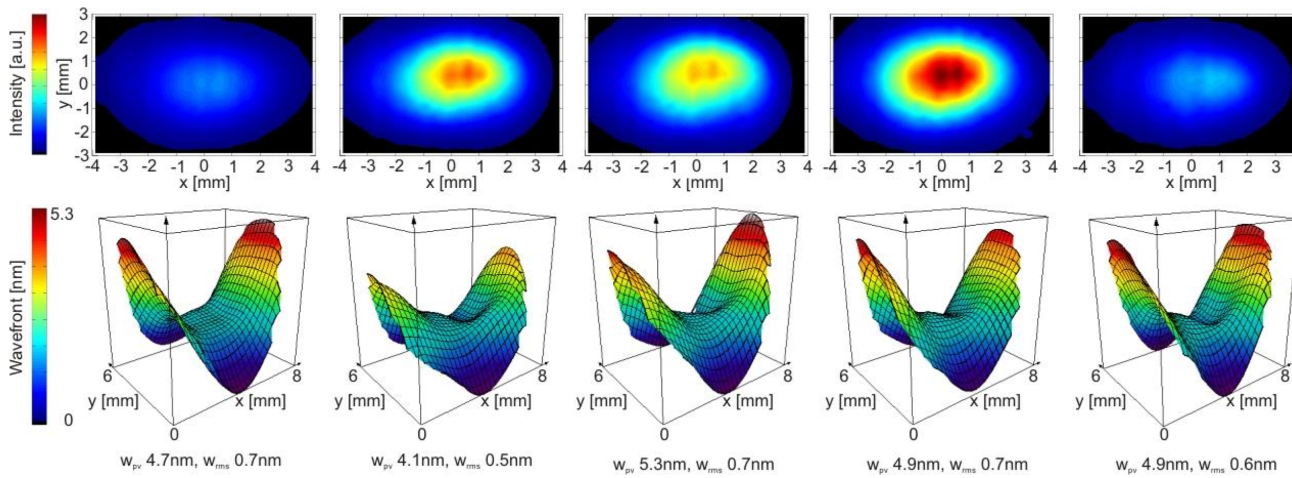
Beam profiles and wavefronts of single pulses (no focusing mirror)



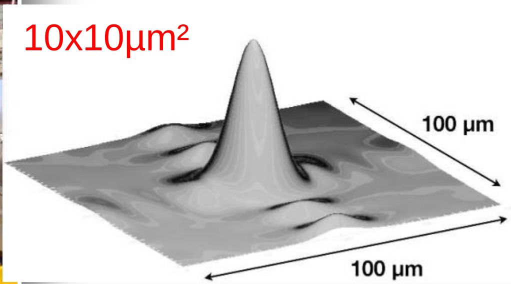


Beam propagation parameters	X	Y	
w_{pv} [nm]	5.3 ± 0.69		✓
w_{rms} [nm]	0.67 ± 0.09		✓
Beam propagation parameter M^2	1.15 ± 0.08		(✓)
Beam propagation parameter M^2_i	1.23 ± 0.1	1.1 ± 0.1	(✓)
Beam width d [mm]	6 ± 0.2	4.4 ± 0.1	✓
Waist position $z_{0,i}$ [m]	-109.2 ± 0.9	-99.2 ± 1.4	✓
Rayleigh length z_R [mm]	3760 ± 484	5090 ± 731	✓
Waist diameter $d_{0,i}$ [µm] 2nd moment	200 ± 20	223 ± 25	(✓)
Divergence θ[µrad]	55 ± 2	44 ± 2	(✓)

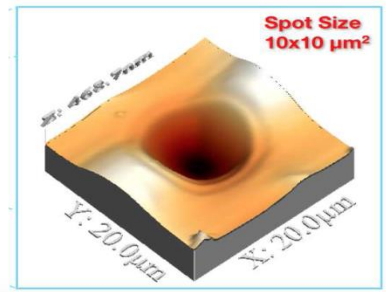
Beam characterization at FERMI@Elettra / Triest @λ = 32nm

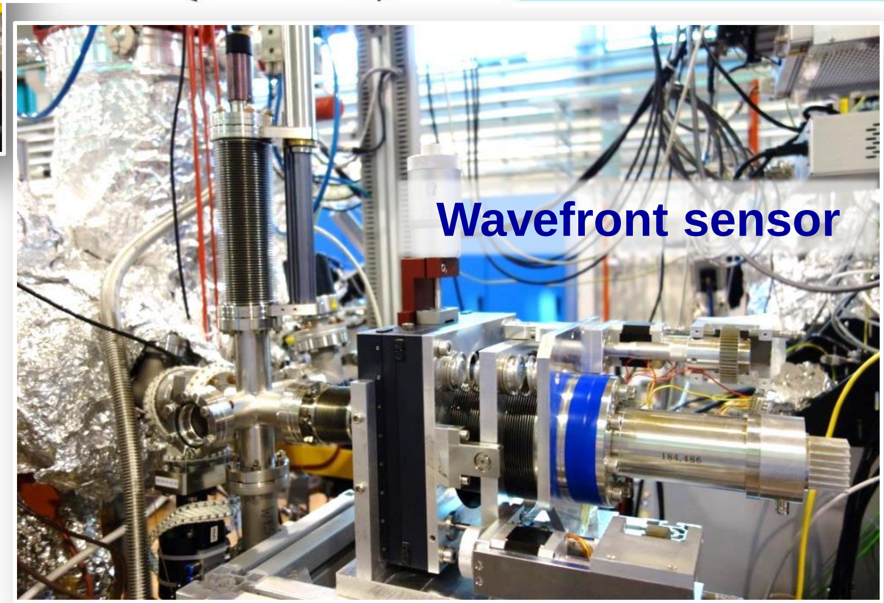
Focal spot size:

Computed



PMMA imprint





Summary:

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- **Laser plasma EUV / soft x-ray source**
  - Clean, stable, compact
  - λ=1…20nm, ns…ps pulses
  - reflectometry, ablation studies, NEXAFS / EXAFS for chemical analysis
  - → spectro-microscopy
- **Hartmann wavefront sensor (EUV / soft x-rays)**
  - real-time alignment of optics
  - beam propagation for single pulses
  - → Characterization of partially coherent radiation ↔ Wigner distribution

Thank You !

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Coworkers:

- *Dr. B. Schäfer*
- *Dr. U. Leinhos*
- *J.O. Dette*
- *W. Hüttner*
- *F. Kühl*
- *M. Lübbecke*
- *T. Mey*
- *M. Müller*
- *G. Steinert*
- *J. Sudradjat*
- *M. Stubenvoll*

SFB 755
Nanoscale Photonic
Imaging

XUV peak brillance of laser plasma source

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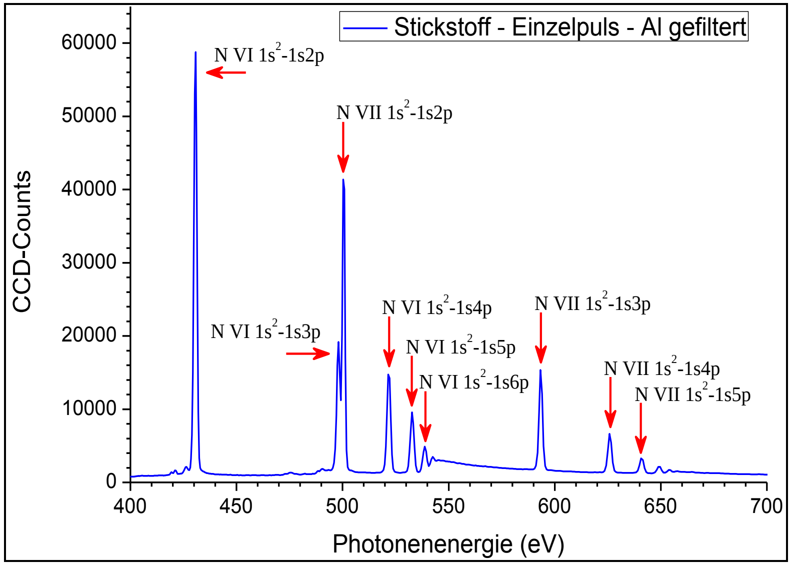
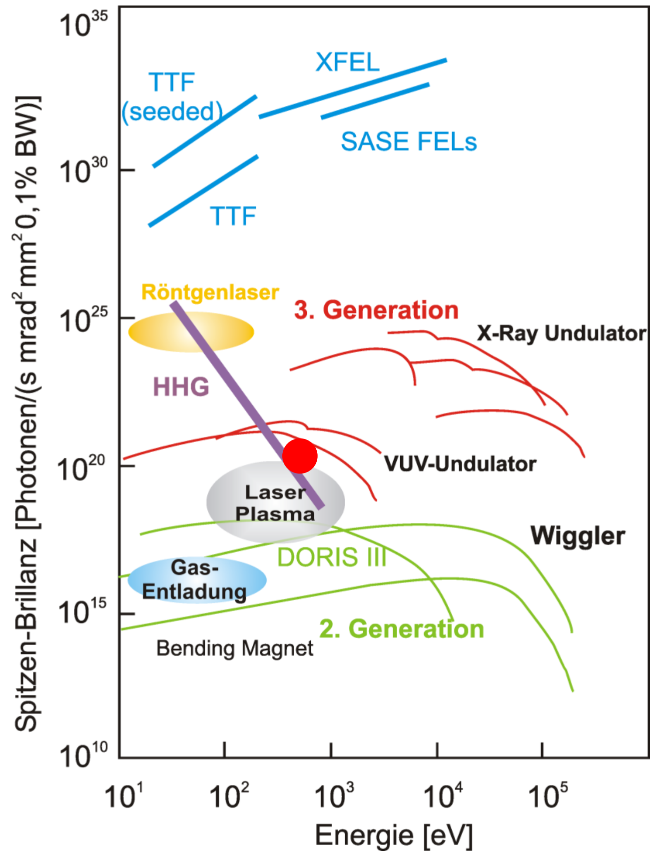


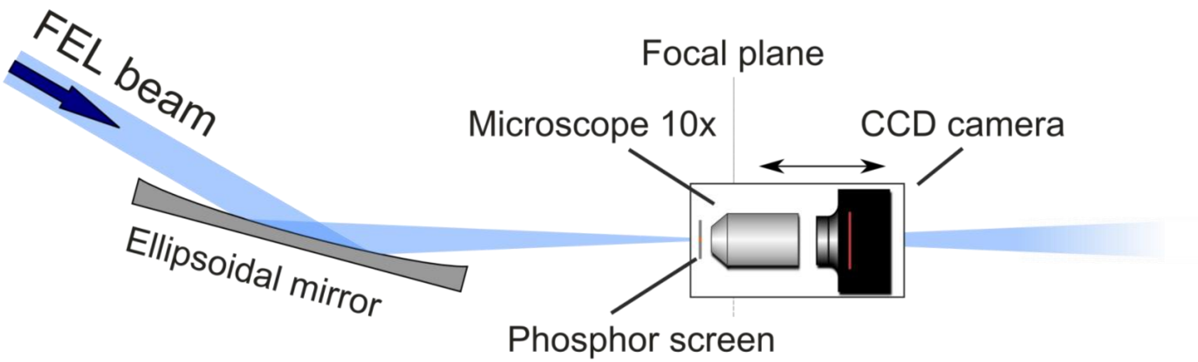


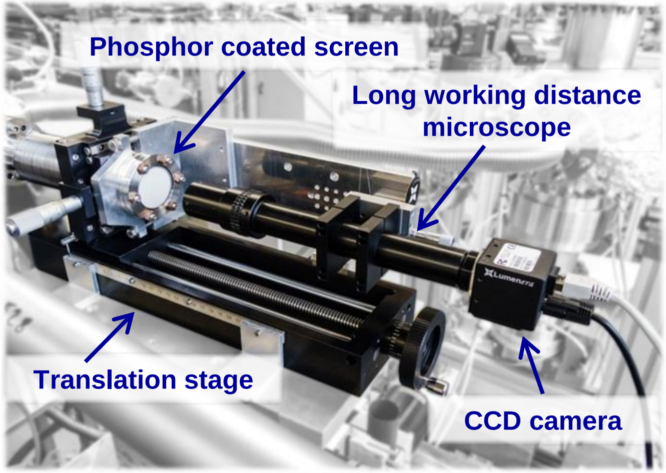
- Isolated **N VI 1s²-1s2p** line @ 2.8787nm (Ti filtered)
- Peak brillance *[Photons/(s mrad² mm² 0,1%BW)]*
  - *ns laser: $6*10^{17}$ (LLG, T. Wilhein)*
  - *ps laser: $1,2*10^{20}$ (LLG)*

- *Brightness (ps): ~10^{14} photons/(pulse x sr)*

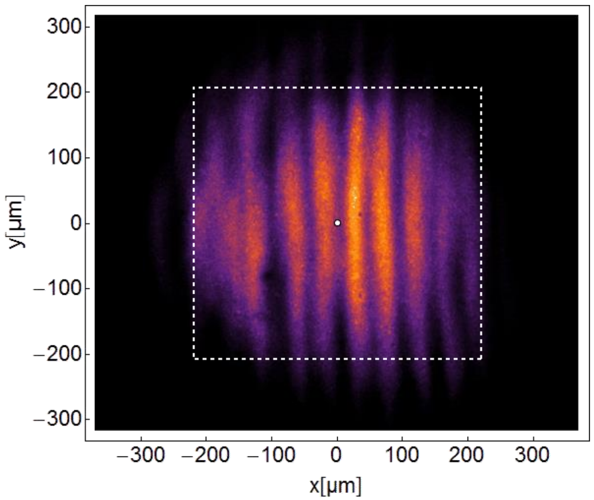
Comprehensive beam characterization → **Wigner distribution**
= Fourier transform of Mutual Coherence Function

Caustic of FLASH:

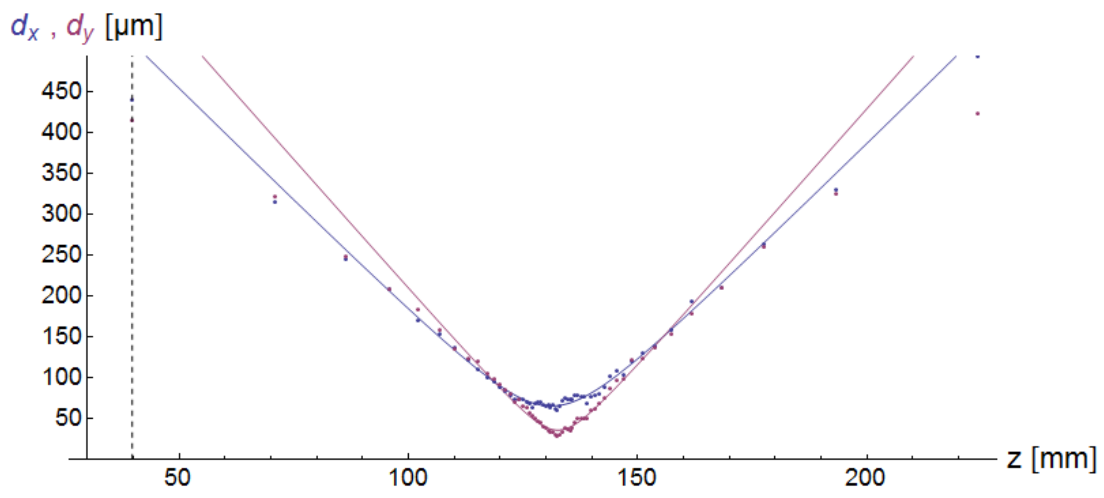




Intensity distribution



Beam diameter



Determination of Wigner distribution function

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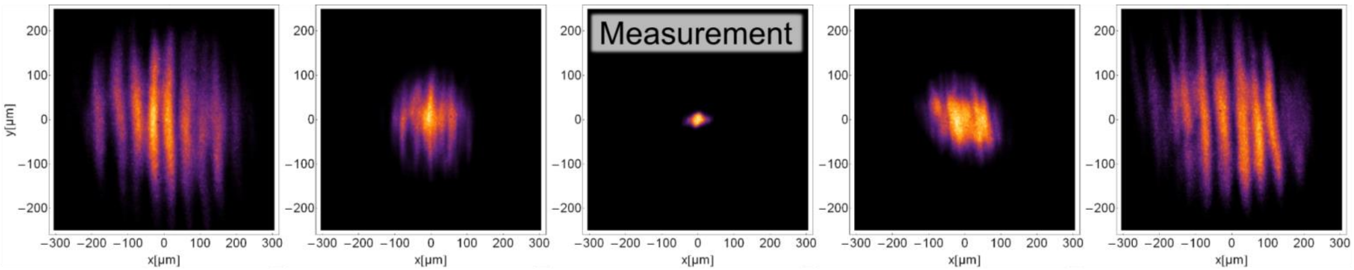
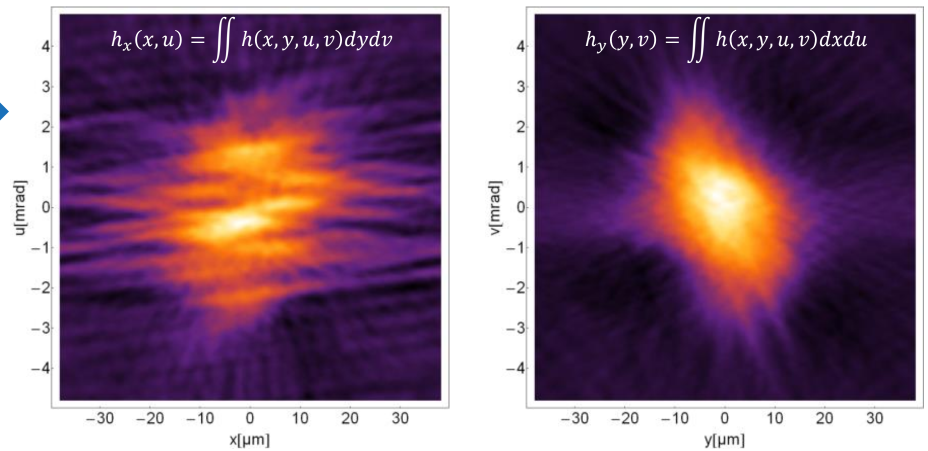


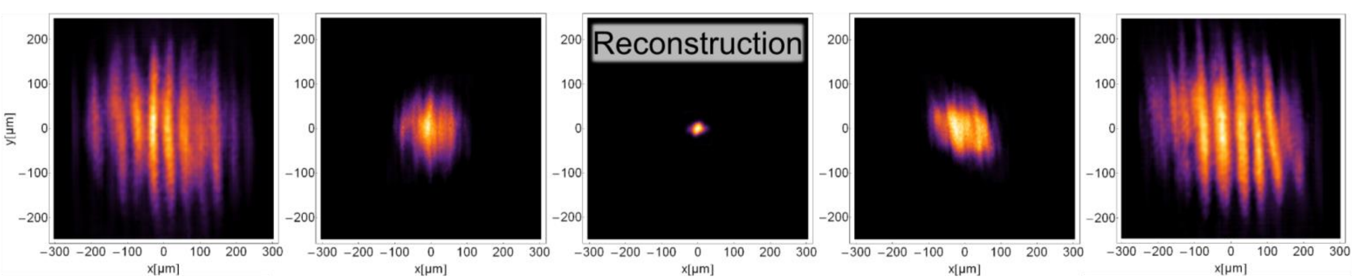
mapping measured data into 4D Wigner Fourier space

FFT

- Wigner distribution function



Reconstruction of beam profiles

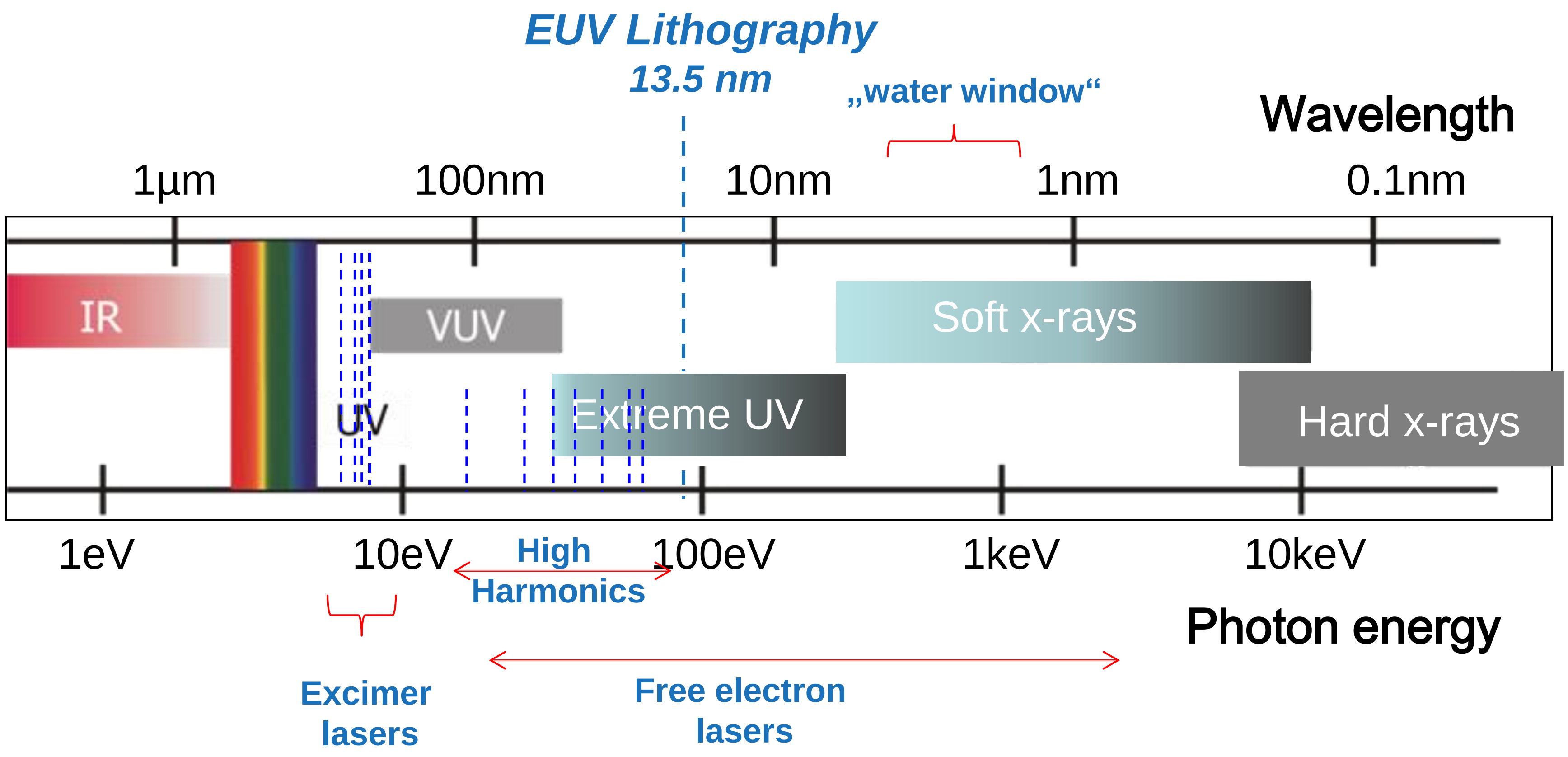


$\Rightarrow$ **comprehensive beam characterization**

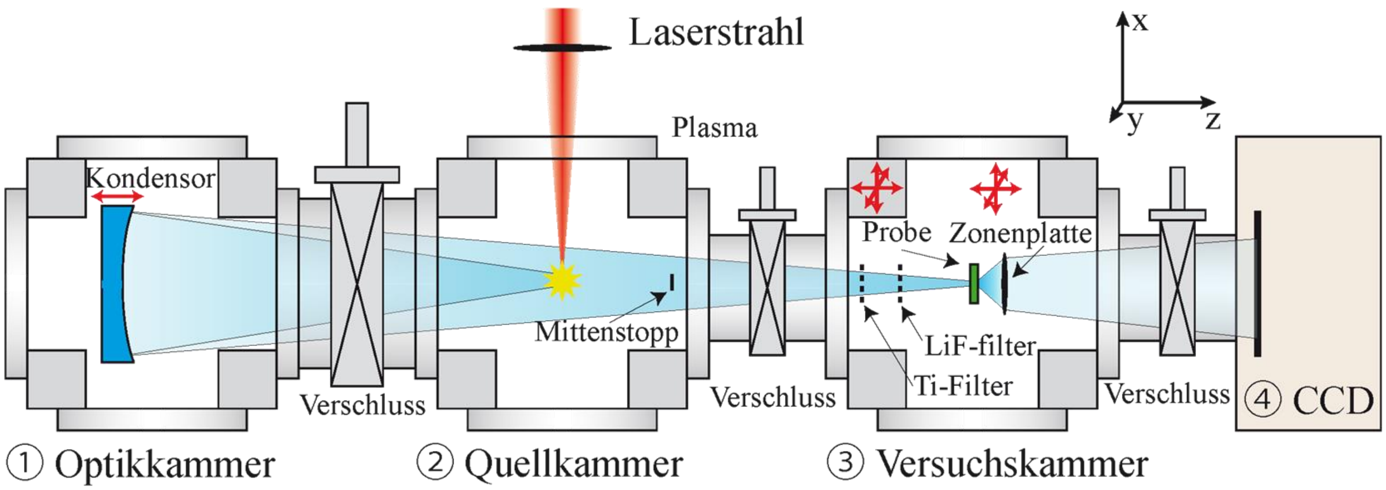
- *beam parameters*
- *coherence function*
- *mode content*
- *wavefront*
- *angular characteristics*

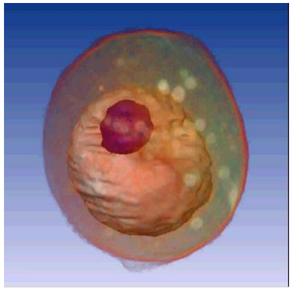
B. Schäfer, T. Mey, K. Mann, K. Tiedtke et al, Nucl. Inst. Meth. 2011

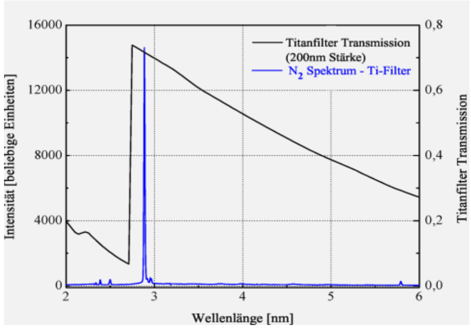
Spectrum of electromagnetic radiation



Kompaktes Labor-Röntgenmikroskop

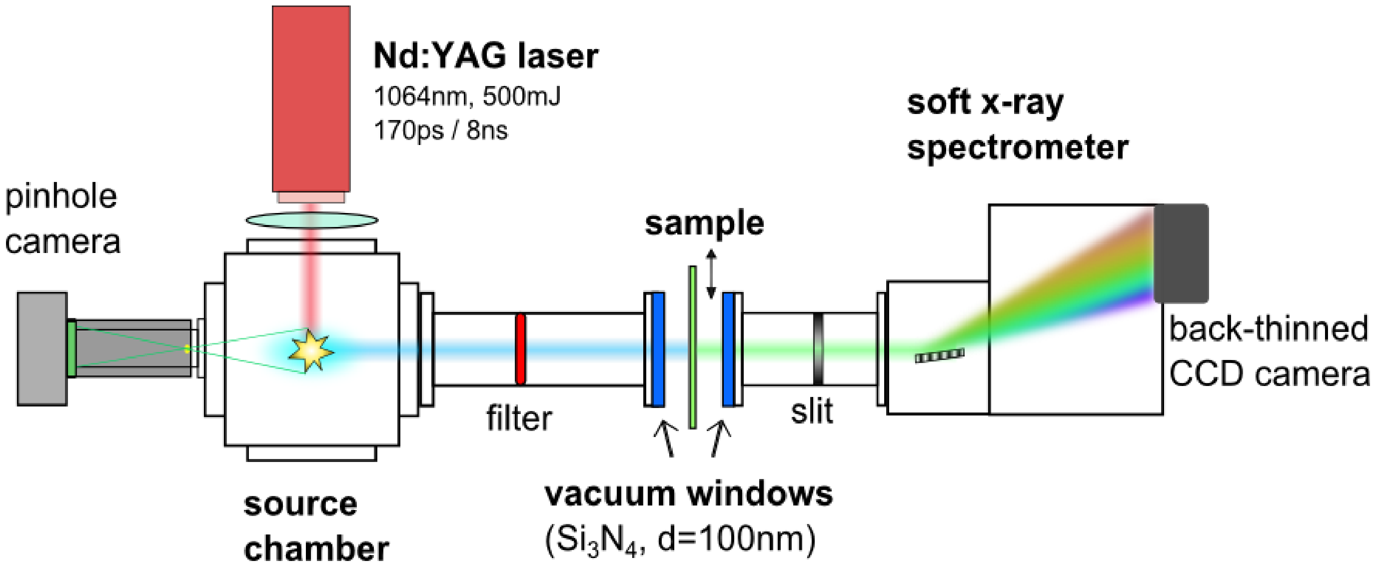




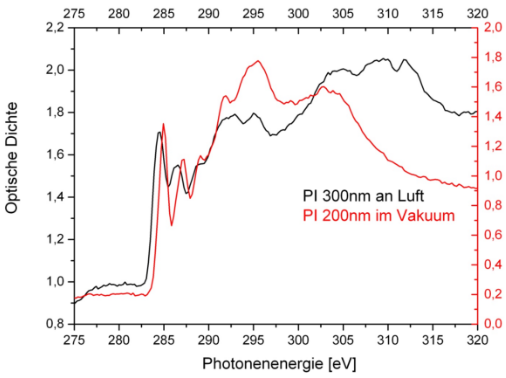


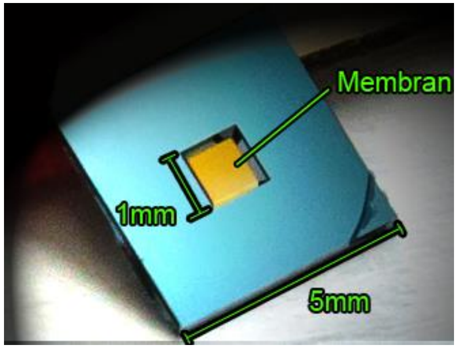
- Gepulstes Hochdruck-Gastarget
- A) monochromatische Strahlung @λ=2,88nm (N_2 + Ti-Filter)
- B) Bichromatisches Konzept zur elementspezifischen Mikroskopie um die Ca-Kante (λ=3,58 nm)
- **→ Spektro-Mikroskopie**

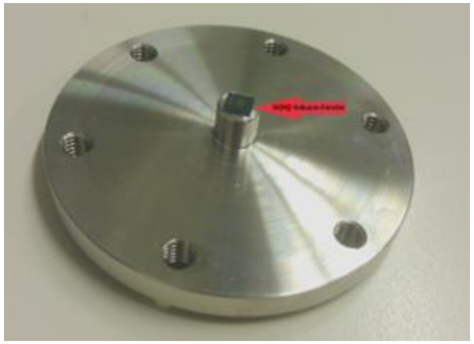
NEXAFS measurements at athmospheric pressure

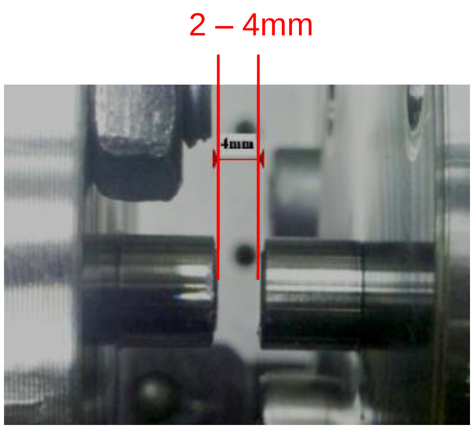


Polyimide:









Improvements (2):
Plasma generation with barrel shock

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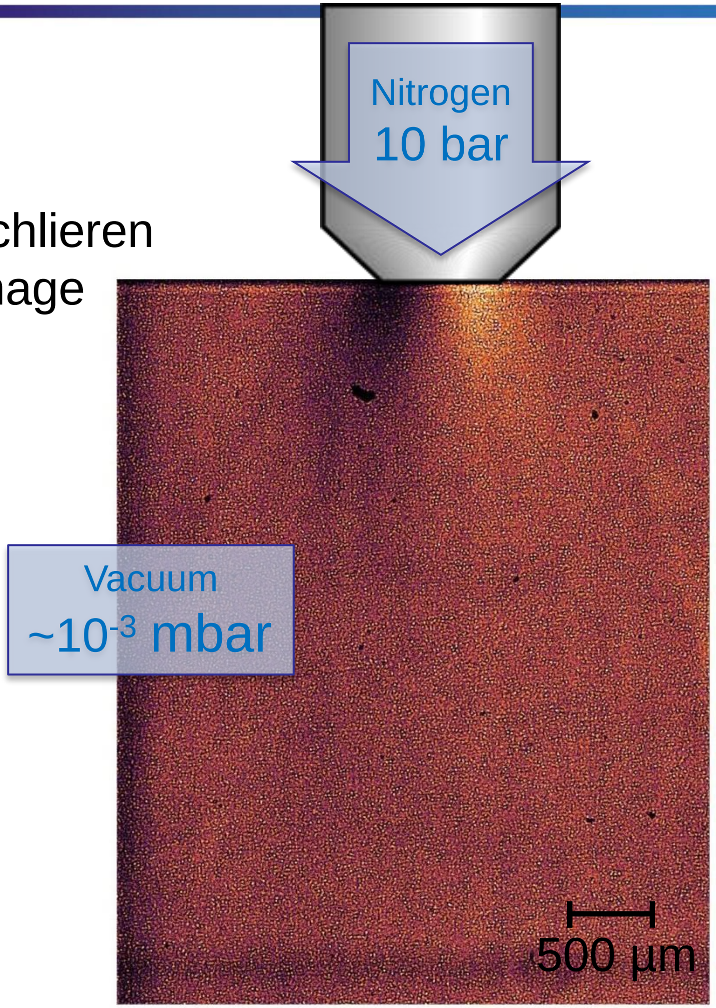
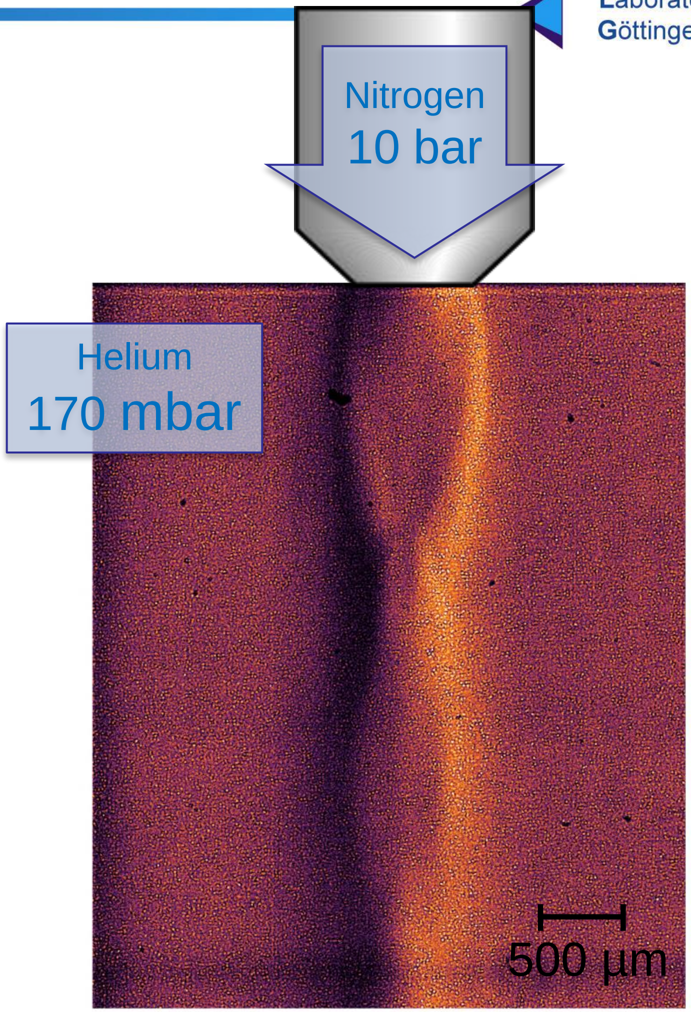
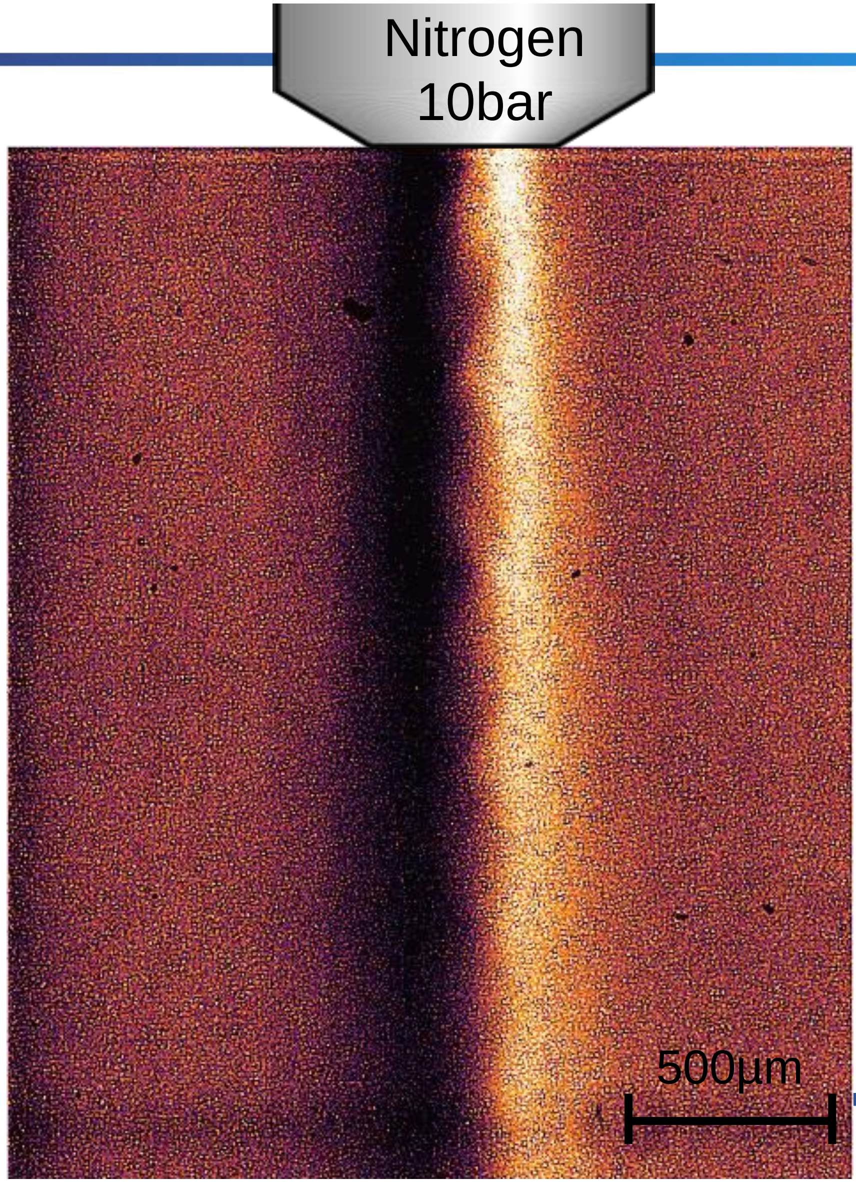
Schlieren image





Improvements (3): Barrel shock

Schlieren images:



ambient pressure:

1 bar

10^{-3}mbar

Beam characterization:

Hartmann-Shack wavefront sensor

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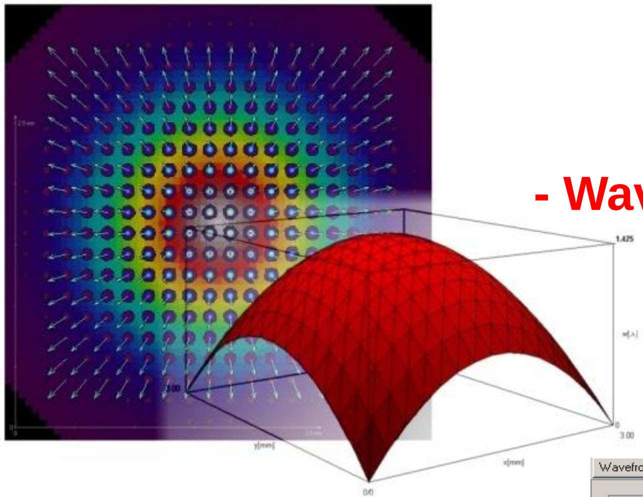
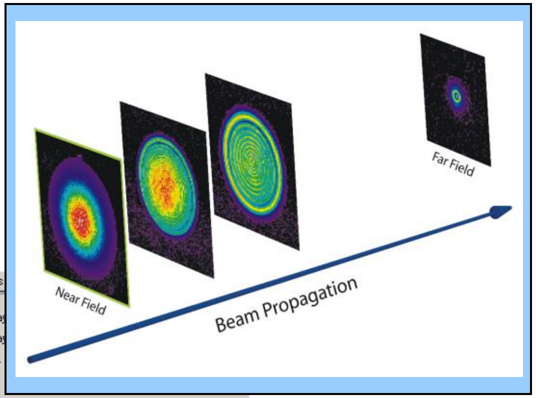
Spot distribution → **- Beam profile**

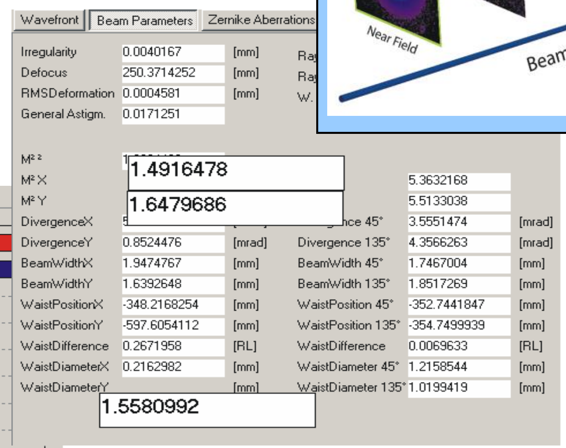
- Wavefront



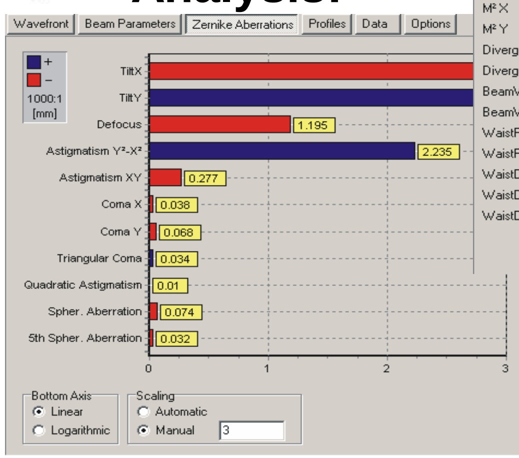
Propagation analysis



Beam parameters:



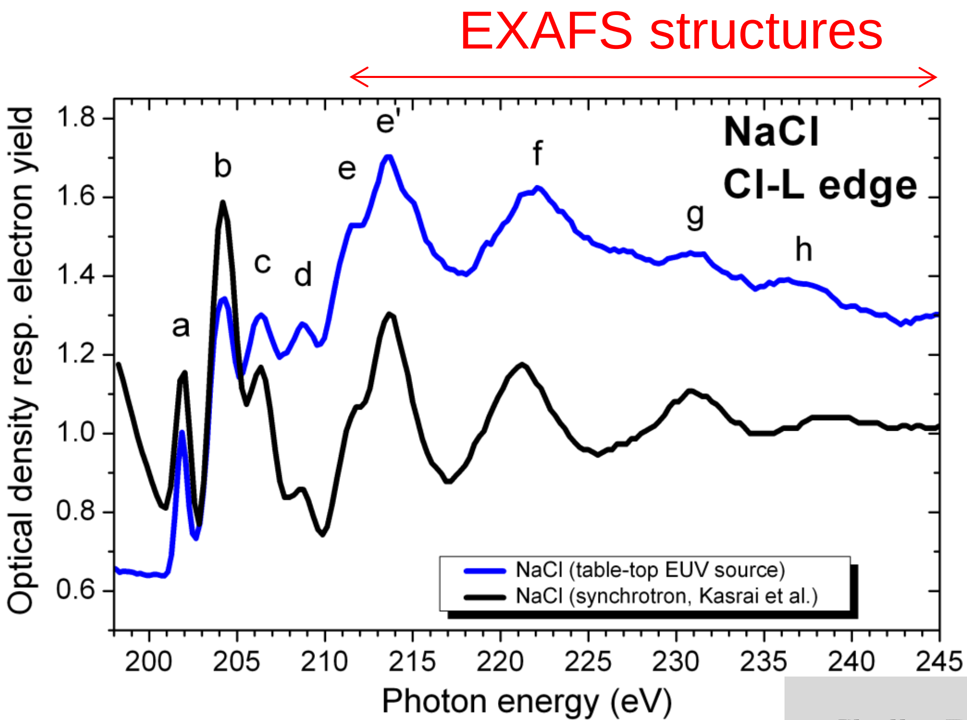
Zernike Analysis:

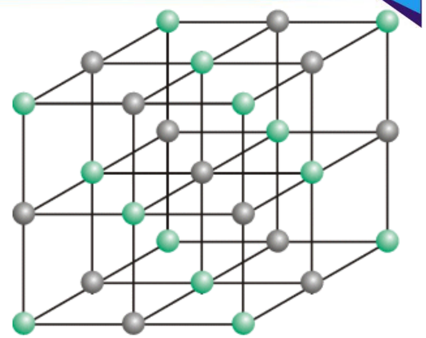


$$M_x^2 = \frac{4\pi}{\lambda}\sqrt{\left\langle x^2\right\rangle\left\langle \beta^{x2}\right\rangle - \left\langle x\beta^x\right\rangle^2}$$

B.Schäfer, K. Mann, Rev. Sci. Instr. 77, 053103 (2006)

EXAFS: Cl L-edge of NaCl





- 200nm NaCl film
- L-edge of Cl (EUV range)
- **Bond lengths:** Excellent agreement with Synchrotron data

$$R_i = \sqrt{\frac{C}{E_i - E_{Streu}}}$$

Shell	Peak	R[Å] Fit.	R[Å] gemessen	R[Å] Kasrai
R1	h	2,82	2,86	2,85
d_{111}	g	3,26	3,18	3,18
R2	f	3,99	3,88	3,85
R3	e	4,88	5,13	5,02

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Results and discussion I - Overview

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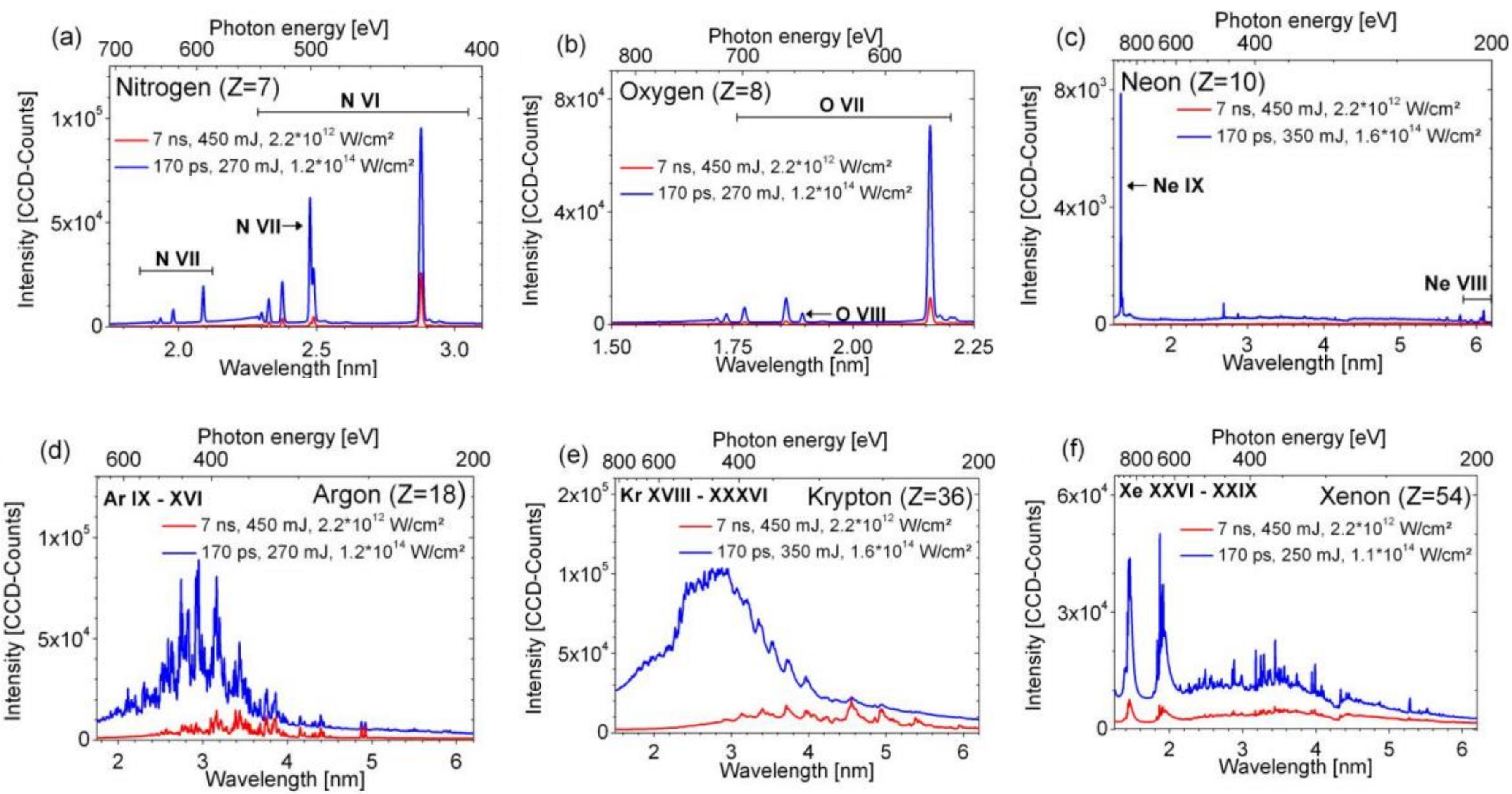

Results and discussion III – different pulse energies

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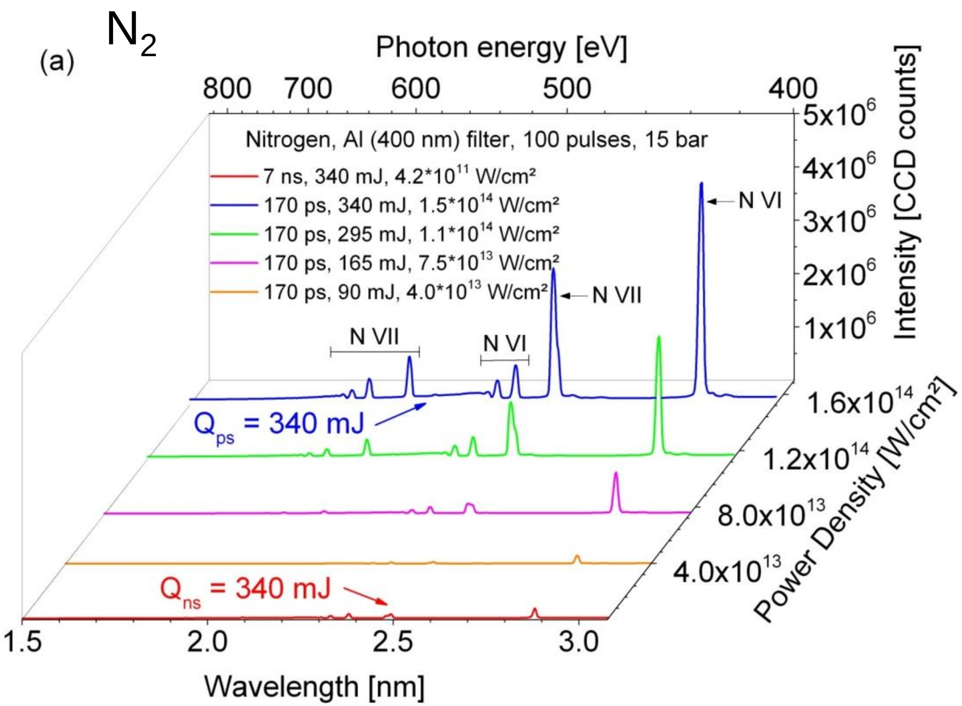

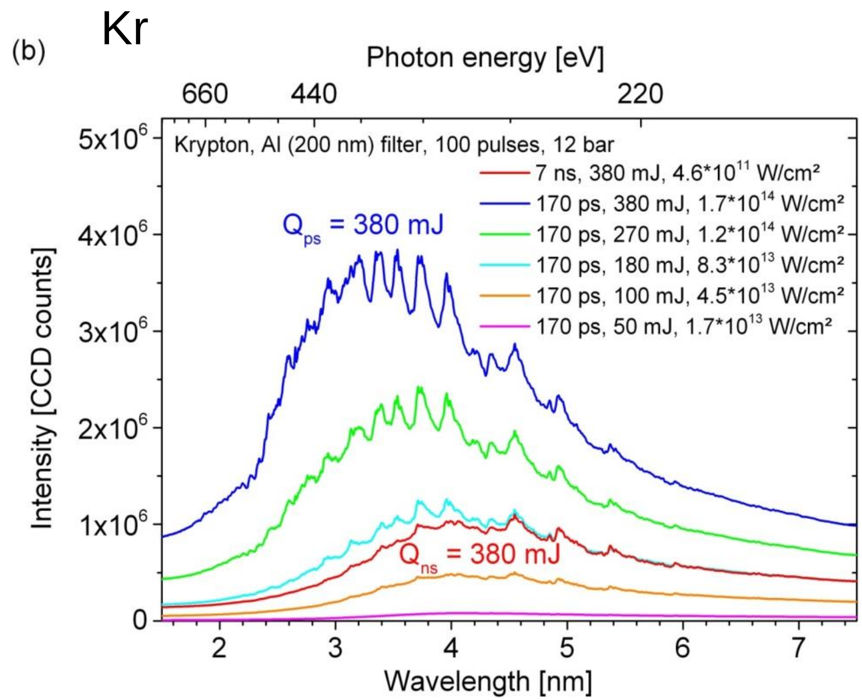

The higher emission intensity of the ps plasma and shift to shorter wavelengths (considering the same pulse energy of ns and ps laser) is attributed to the higher electron density and higher electron temperature, respectively.

Results and discussion VI

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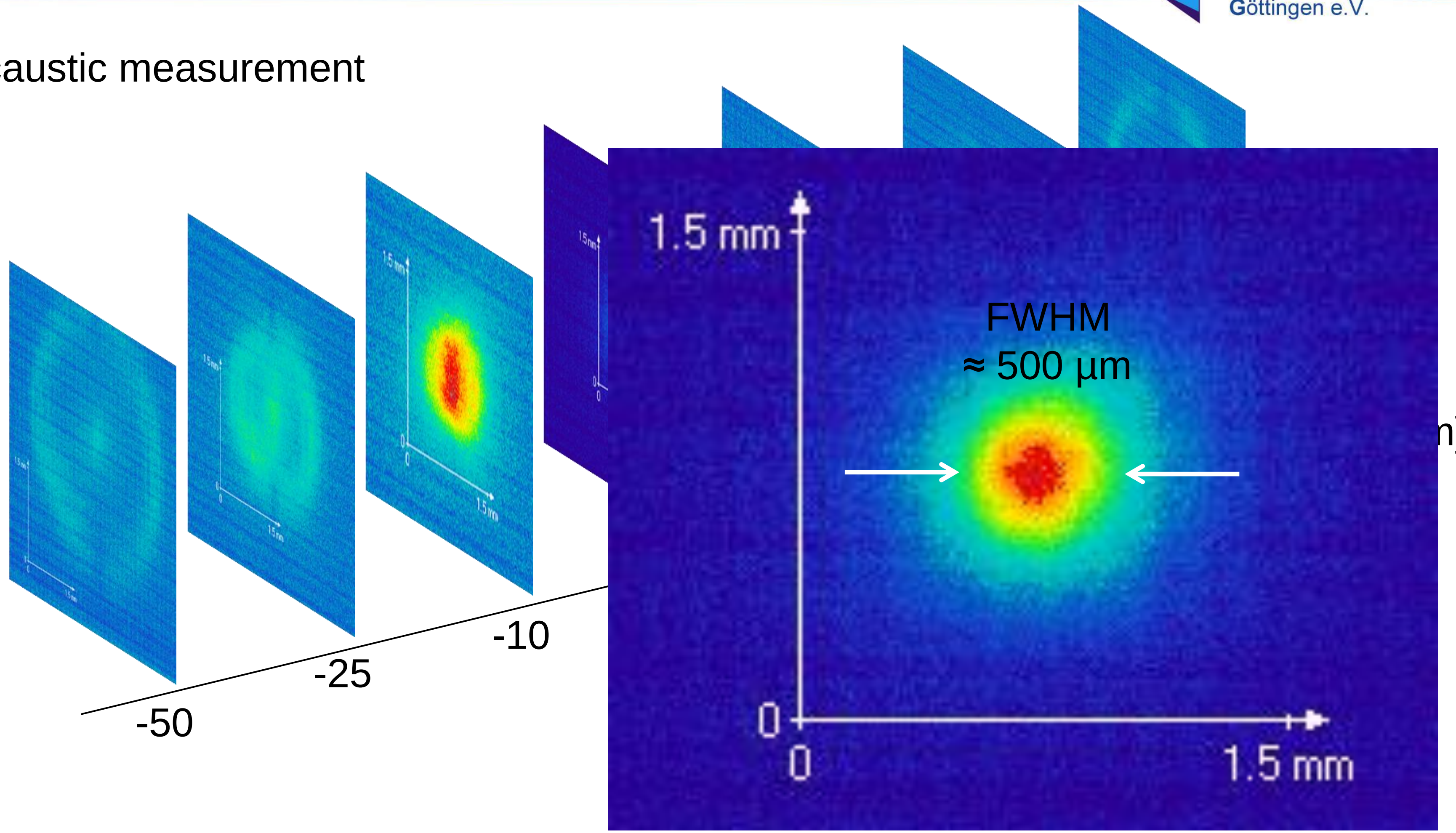
Parameter	ns laser	ps laser
Wavelength (λ)	1064 nm	1064 nm
Pulse duration (τ) (FWHM)	7 ns	0.17 ns
Laser pulse energy (Q)	450 mJ	380 mJ
Diameter of focal spot	30 µm	20 µm
Maximum power density	2.2×10^{12} W/cm²	1.7×10^{14} W/cm²
Plasma size	470 µm x 190 µm	310 µm x 150 µm
Brightness	5×10^{12} photons/(pulse x sr)	8×10^{13} photons/(pulse x sr)
Peak Brilliance @ 2.88 nm	1×10^{15} photons/(s x mrad² x mm²)	4×10^{18} photons/(s x mrad² x mm²)

Soft x-ray microscopy II

- caustic measurement



Soft x-ray microscopy III

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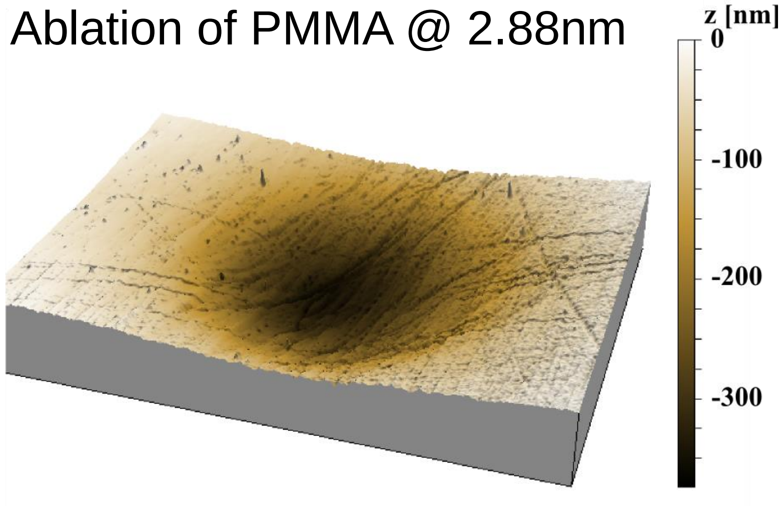
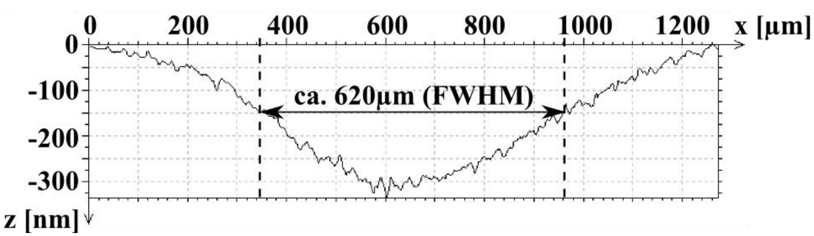
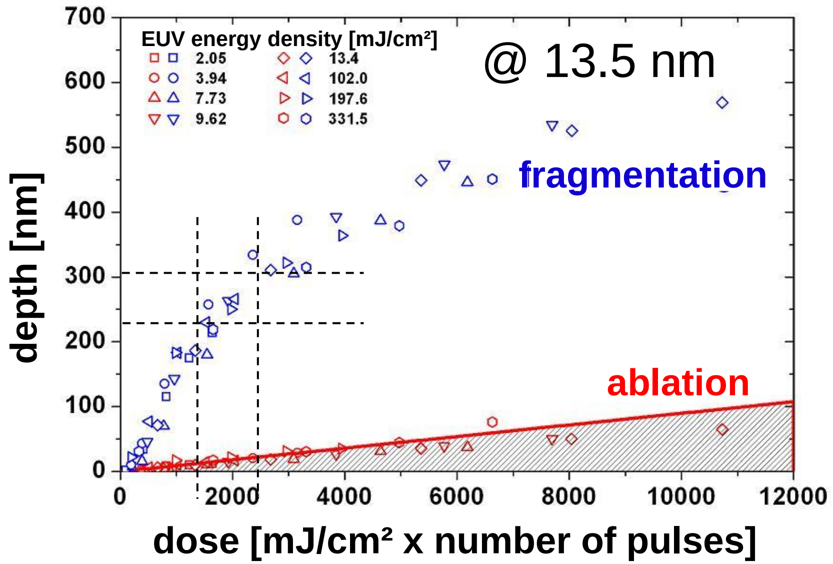
- Ablation of PMMA @ 2.88nm







5000 pulses, N_2 @ 15 bar,
3 min ultrasonic bath

⇨ energy density between 0.3 mJ/cm² - 0.5 mJ/cm² @ 2.88 nm in the focal spot of the elliptical mirror

⇨ ≈ 8.5*10⁹ photons/pulse

Soft x-ray microscopy IV

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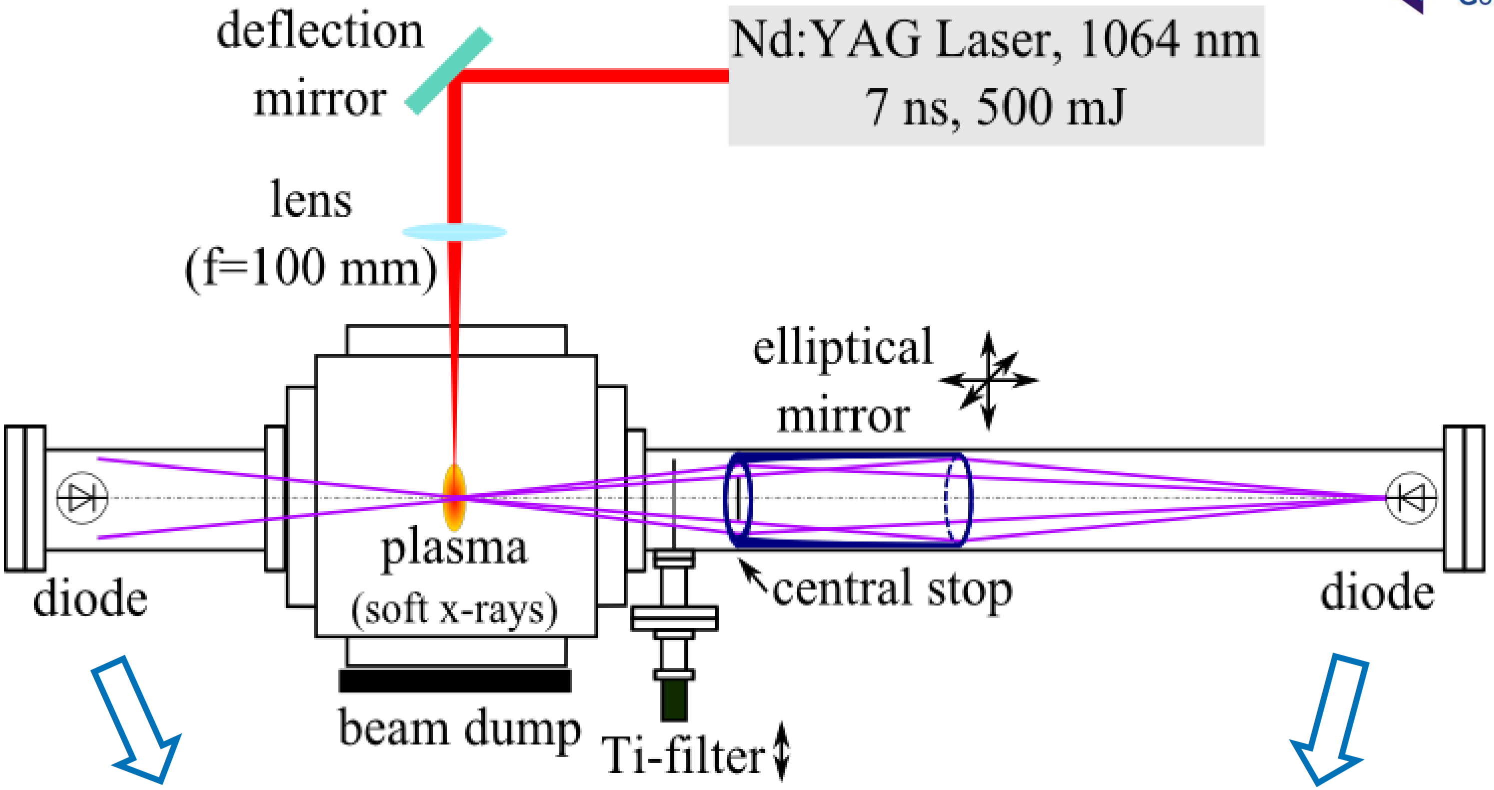

2.3*10^{12} photons/(sr*pulse)

1.8*10^{11} photons/(sr*pulse)

⇨ R ≈ 8%

Caustic of HHG Source

25. Harmonic (λ=32nm)

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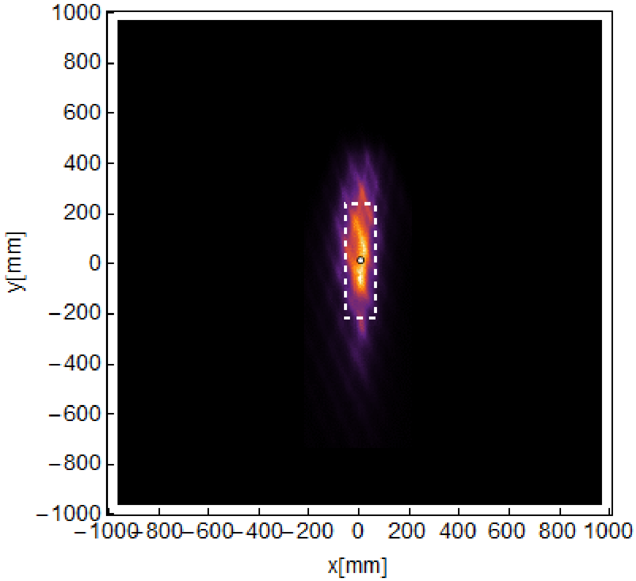

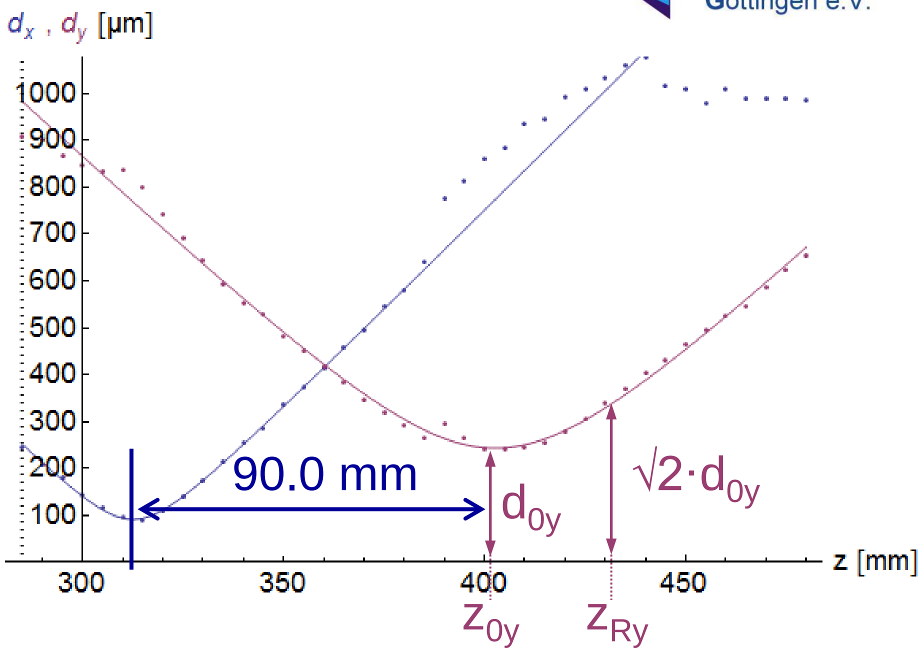

		x	y
Waist diameter	d_0	91.5 µm	243.4 µm
Waist position	z_0	312.6 mm	402.6 mm
Rayleigh length	z_R	10.7 mm	30.1 mm
Beam propagation factor	M^2	19.7	50.0

↔ Aberrations !

Real-time wavefront measurement

25. Harmonic (λ=32nm)

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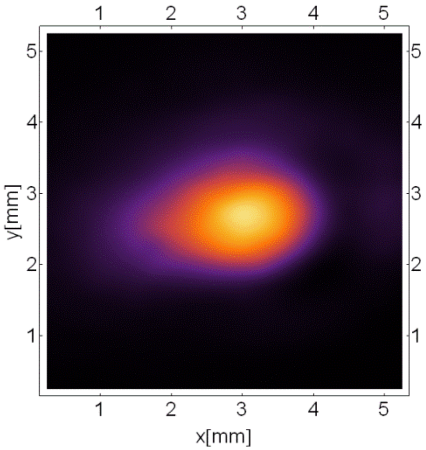
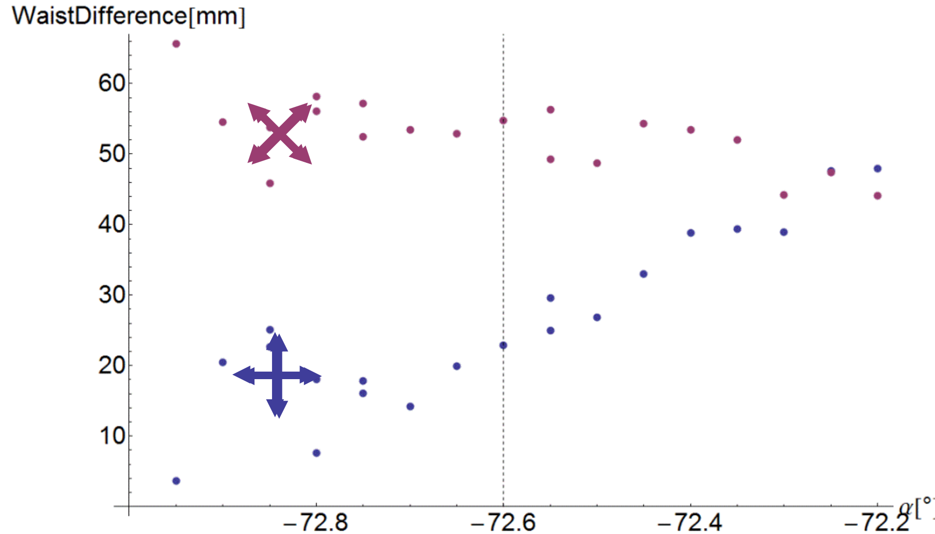
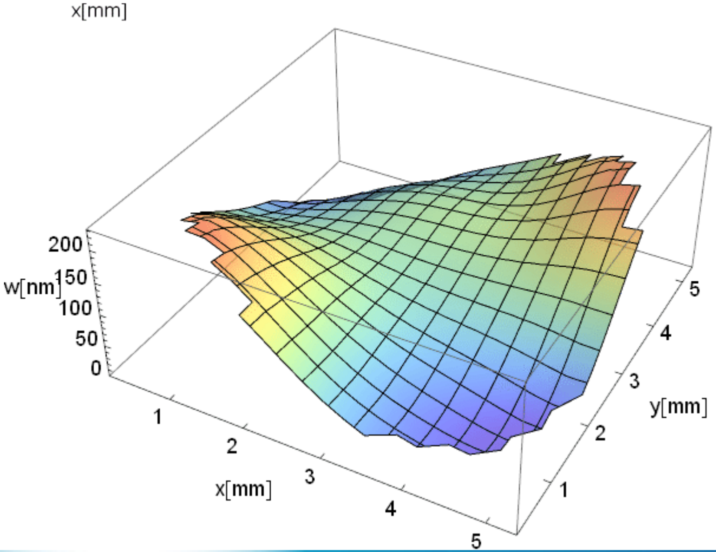
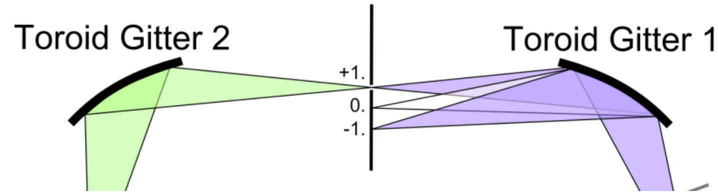


Yaw angle

$$\boxed{\alpha = -72.95^\circ}$$

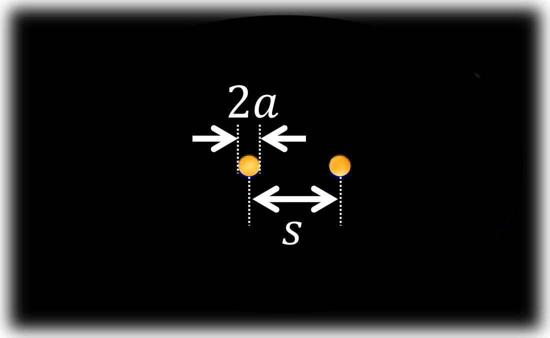






→ Pitch angle !

Spatial coherence:

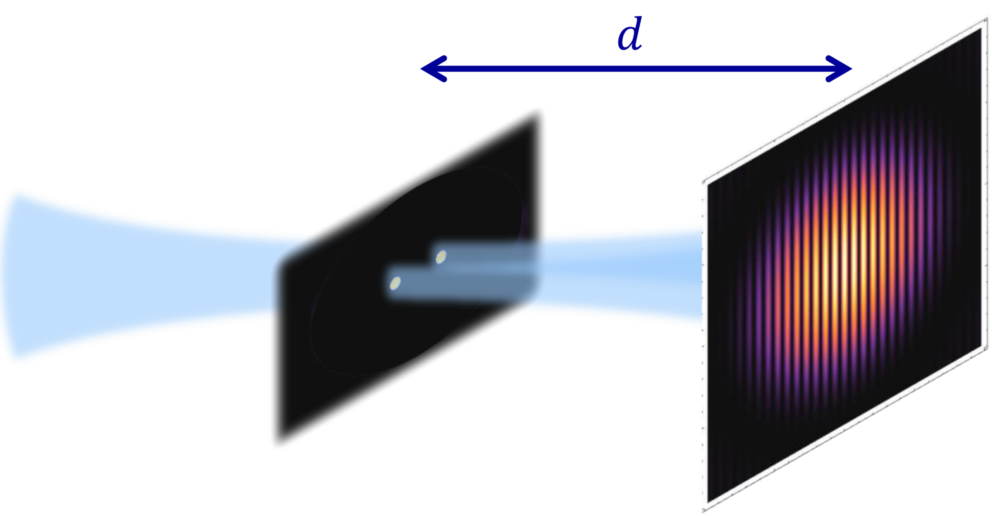


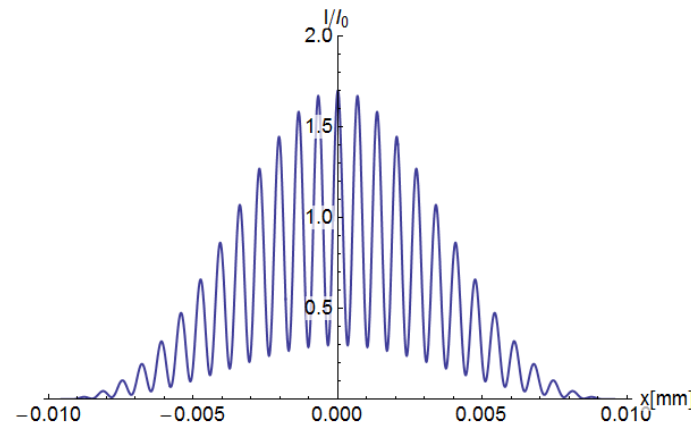
Young´s experiment:

interference of elementary waves

Contrast of fringes

→ local degree of coherence $\gamma(\vec{x}, \vec{s})$:





Caustic of Free Electron Laser FLASH / DESY

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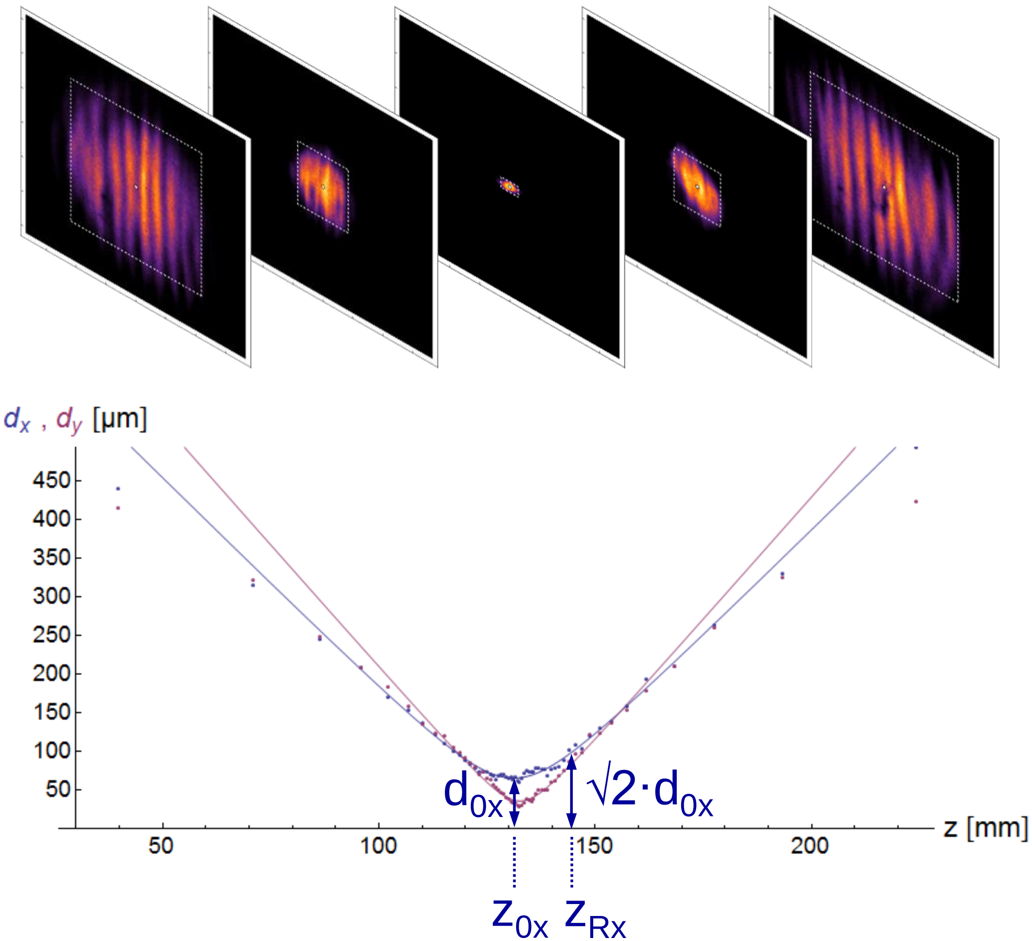
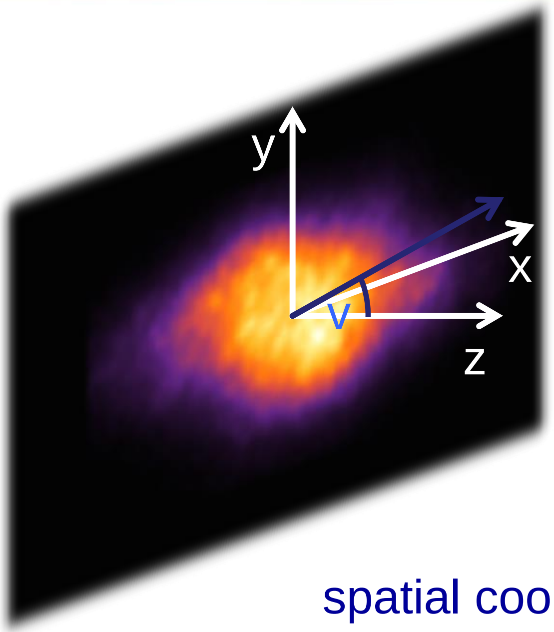


Beam parameter	Value
Waist position z_{0x} / z_{0y} [mm]	131.1 / 132.6
Waist diameter d_{0x} / d_{0y} [μm]	65.5 / 35.9
Rayleigh length z_{Rx} / z_{Ry} [mm]	11.8 / 5.7
Beam propagation factor M^2_x / M^2_y	21 / 13
coherence	???

Wigner distribution



h = Fourier transform of Mutual Coherence Function:

Wigner distribution

mutual coherence function

$$\boxed{h(\vec{x},\vec{u}) = \left(\frac{1}{2\pi}\right)^2 \cdot \iint \Gamma(\vec{x},\vec{s}) \cdot e^{-i\vec{u}\cdot\vec{s}} d^2 s}$$

spatial coordinate $\vec{x} = \binom{x}{y}$

angular coordinate $\vec{u} = \binom{u}{v}$

Interpretation: radiance at position $\vec{x}$ in direction of $\vec{u}$

$$[h] = {}^{\mathrm{W}}\!/_{\mathrm{m}^2 \cdot \mathrm{sr}}$$

M. J. Bastiaans, 1986, *Opt. Acta* **28** 1215-24